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Threshold adaptation, temporal integration and frequency discrimination-learning in hearing impaired children

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THRESHOLD ADAPTATION, TEMPORAL INTEGRATION AND FREQUENCY DISCRIMINATION-LEARNING IN HEARING IMPAIRED CHILDREN

by

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CHAPTER I

INTRODUCTION

The process of teaching a child to make maximum use of his ability to hear, called auditory training, is especially important for a child with a severe hearing disorder because he does not learn to attend to sound as readily as does a child with normal hearing. Because of his reduced sensitivity he cannot hear most environmental sounds, including speech. As a consequence, unless he is taught to attend to sound, he may remain functionally deaf. That is, he might learn to ignore even those sounds that he is able to hear in much the same way that a child with normal sensitivity learns to ignore meaningless sounds.

A less severe possibility is that he might learn to recognize and attach meaning to only a small number of sounds. Without training, he might not realize that subtle variations in the sounds that he can hear contain information which, by careful attention, he could learn to discriminate and recognize.

Amplification offers the possibility of making the spectrum of environmental sounds, including speech, at least partially audible to the hearing-impaired child. However, amplification alone has several limitations. One limitation is fixed by the amount of loss of sensitivity. The lower boundary or minimum of amplification is set by the threshold of sensitivity. Amplified sound must be more intense than the threshold level. The upper boundary is set by the threshold of discomfort (Silverman, 1947). Above this level the sound may be intolerably loud or cause actual physical discomfort, even pain. Clearly, all amplified sound must fall between these two thresholds. For a severely hearing-impaired child, this intensity range can be small.

In the frequency domain, there are also limitations in range. While some hearing-impaired children have residual hearing up to 4000 Hz, others have little or no hearing above 1000 Hz. For these latter children, only a limited spectrum of amplified sound can be made audible.

A second limitation of amplification is fixed by the characteristics of the hearing disorder. Assume that a sound is delivered above threshold and the hearing-impaired child makes a specified response. Will his response to this sound be similar to that of a child with normal hearing? A large body of data gathered from hearing-impaired adults indicates that some types of responses to sound might be normal while others might not. Whether the response is normal or not depends on both the characteristics of the stimulus and the anatomical and physiological disorders which cause the hearing impairment.

A third limitation of amplification is set by the effect the sound has on the listener. While amplified sound might produce an auditory sensation within the listener, the individual sound must be discriminated from other sounds, recognized as having been heard before, and associated with meaning, if the amplified sound is to have significance. Therefore, the child requires auditory training as well as amplified sound.

Auditory training has four aspects (Carhart, 1960), all of which are carried on more or less concurrently. As alluded to before, one aspect involves teaching an awareness of sound and teaching the idea that the sensation of sound is a meaningful experience. This is done, for example, by pairing the mother's voice with cuddling, with food, and with other positively reinforcing activities.

Another aspect is teaching the child that different objects produce different sounds; that is, teaching gross discrimination. For example, the child is shown and allowed to hear a bell and a drum. The devices are then hidden; one of the sounds is delivered; and the child must judge which object produced the sound.

A third aspect is teaching finer discriminations. For example, the child is required to differentiate tones played on the piano or to differentiate between vowel sounds uttered by the teacher. If the child has usable hearing up to 4000 Hz or more, an attempt can be made to teach him to discriminate between consonants. The consonants are generally more difficult to discriminate than vowels because they contain less acoustic energy and are of shorter duration.

The fourth aspect is teaching the child to recognize words and to pair meanings with them. This last process is done in much the same way that a child with normal sensitivity is taught a second language.

Although the general plan of auditory training is simple, in practice, the degree of success of auditory training is difficult to predict. There are wide differences in performance between children. Some children learn to discriminate sounds very slowly even after years of training. One author has suggested that auditory training has been generally so unsuccessful that it should be abandoned and that sign language should be taught as the chief communication avenue for deaf children (Kohl, 1966). This suggestion is premature.

One constructive criticism of auditory training can be directed at the lack of control over the physical dimensions of the stimuli used. Bells, drums, horns, the piano, and the human voice have been used. The exact physical characteristics of the sounds produced by these devices are not known by the teacher, and she does not have exact control over them. Thus, when she delivers a particular stimulus to a child and he indicates he recognizes it, she does not know precisely along which dimension of sound he is responding. For example, the acoustic dimensions of a pure tone are frequency, amplitude, and duration. In a typical classroom situation, two sounds might be alternately delivered which differ along all three dimensions at once. While one child might respond to differences in amplitude, another might respond to differences in frequency or duration.

Environmental sounds like speech are much more complex than pure tones. For example, speech sounds contain many frequencies. The amplitudes of the component frequencies are different for each phoneme. Furthermore, amplitude and frequency are often changing as different phonemes are strung together into words and phrases. The amplitude of a specific frequency changes at different rates depending upon the phoneme being uttered and the phoneme which preceded and follows it. Frequency spectrum also changes at different rates depending upon the phoneme being uttered and those which come before and after it.

Clearly there is a number of cues available by which a child might identify a particular sound. Within a group of hearing-impaired children, each child might respond to a different cue. The end result of auditory training, using inadequately controlled stimuli, could be that although all the children learned to recognize a particular sound, performance would still be heterogeneous because each child responded to a different aspect of the stimulus. In contrast, delivery of carefully specified and controlled stimuli might result in a much better understanding of what a particular child is learning or failing to learn during auditory training.

When stimuli are carefully specified and controlled, it is possible to study how variations in a single stimulus dimension affects the response of the hearing-impaired child. For example, a large body of data gathered from listeners with normal hearing shows that duration affects sensitivity for sound (Zwislocki, 1960; Olsen & Carhart, 1960), the perceived loudness of sound (Miller, 1948), and the discriminability of two slightly different frequencies (Turnbull, 1944; Chih-an & Cristovich , 1960). The frequency of a tone affects both threshold sensitivity and the rate at which loudness increases above threshold (Stevens & Davis, 1938). Amplitude, at least up to a certain level, affects the discriminability between two frequencies (Harris, 1952a).

Some of the effects of variations of stimulus dimensions on response have also been studied in listeners with impaired hearing. Generally these listeners show greater heterogeneity of response than do normal listeners. In addition, they sometimes show responses which do not occur among normal listeners. Furthermore, they show atypical, but uncorrelated responses between one dimension of sound and another (Harris, Hanes & Myers, 1958).

The implication of the work done with hearing-impaired listeners is that each hearing disorder is partly unique and therefore each person has a unique set of disabilities as well as abilities. Possibly the auditory training of a child could proceed more systematically if his responses to different sound parameters were better understood. Failure to learn might be due to inappropriate stimuli rather than inappropriate teaching methods.

Finally, the lack of knowledge about and control over the dimensions of the stimuli used in auditory training makes it difficult to evaluate performance over time. Because the stimuli are not exactly alike from day to day, the possibility exists that the child responds to different cues on different days. What appears as random behavior to the teacher may simply reflect the child's attempt to cope with a poorly defined and continuously changing auditory environment. In contrast, when stimuli are well controlled, discrimination or recognition behavior might achieve stability. Learning curves could then be plotted. In essence, the classroom could become a miniature laboratory where stimulus-response relationships are studied and learning can be quantitatively measured.

A. Statement of the Problem

The purpose of the present investigations was to evaluate the usefulness of the laboratory approach to auditory training with hearing-impaired children. Preliminary investigations were made in two areas.

1. Problem I: Effect of Duration on Sensitivity

Both the audibility and the loudness of a sound build up as stimulation is prolonged over very short periods of time. For these short intervals, instantaneous amplitude is not the sole determiner of response, but rather a quantity, more like energy, which is integrated up to a certain critical duration. On the other hand, as stimulation continues for longer periods of time, particularly loud sounds show adaptation, that is a reduction of activity even for constant amplitude of the signal. Both integration and adaptation yield information about the durational aspects of both normal and impaired auditory systems.

The first problem concerned the effect of duration on sensitivity. It is known that in some hearing disorders, sensitivity is better for interrupted tones than for continuous tones. Furthermore, even normal listeners are less sensitive to tones of a few milliseconds duration than to tones of longer duration. If duration is a significant variable in the sensitivity of hearing-impaired children then this knowledge is essential for specifying both the minimum and maximum durations of stimuli used for auditory training.

To study the effect of duration on sensitivity, two experiments were conducted. The purpose of the first experiment was to compare sensitivity to recurring bursts of sound with sensitivity to a continuous sound. The purpose of the second experiment was to measure sensitivity to tones that were 250, 100, 25, and 10 msec long.

Although some interesting problems emerged from these experiments, their relative significance seemed less than the problems that emerged from Problem II. These experiments therefore receive less emphasis and are reported primarily because they extend present knowledge about hearing impairments in children.

2. Problem II: Frequency Discrimination

The second problem concerned frequency discrimination. This measure of basic discriminatory ability was chosen for two reasons. Some minimum ability to discriminate between frequencies is presumed to be necessary for speech discrimination. This seems especially true for vowel discrimination where the frequency components can attain fairly steady states for as long as 100 to 400 msec (House, 1961).

Second, frequency discrimination is important for monitoring the intonation of one's own voice. Children with poor ability to discriminate frequency might require more intonation practice than children with good frequency discrimination.

The experiment that was conducted estimated the ability of hearing-impaired children to discriminate differences in frequency under a specified set of conditions and with no prior practice under these conditions.

The results of this experiment indicated that auditory training might actually be required before stable performance could be obtained. Therefore, an experiment was designed based on the following considerations. First, does ability to differentiate frequency differences improve with training? Repeated measurements with the same test offered the possibility not only of improving performance by giving practice but also of plotting improvement in test scores. Thus the test itself might become an auditory training device which also gives quantitative information about the child's initial ability and about his performance over time.

A likely outcome of the experiment would be that some children improve in performance while others do not. Are the children who do not improve performing at the limit of their ability or would they improve if given further practice? To answer this question, six of the children who showed large difference limens for frequency (DLFs) in the initial test sessions were given additional tests.

Assuming the test does measure ability to discriminate, is it a valid test of frequency discrimination? If the DLF is large, the possibility exists that the lower (or higher) frequency tone was perceived as being louder and therefore that the subject was actually responding to a systematic loudness cue. Alternatively, the subject might be able to discriminate both dimensions but not understand the concepts of pitch and loudness. It is a common observation that some children confuse amplitude and frequency during their speech training.

To control for a loudness cue, a second test of DLF was given in which loudness differences were deliberately introduced. If at the outset a child did confuse amplitude and frequency, he would have to learn to distinguish between the two cues before he could judge frequency-change correctly better than 50 percent of the time.

Another purpose of this experiment was to re-examine the relation between amount of hearing loss and size of DLF. Possibly the severity of hearing disorder limits ability to discriminate differences in frequency. That is, the greater the disorder, as reflected in amount of loss of sensitivity, the larger the DLF. An alternate hypothesis is that the more important factor is learning. According to this hypothesis, poor initial performance from children with large losses in sensitivity would be due to their limited opportunity in the past to make fine frequency discriminations. Therefore, children with severe hearing losses might initially show larger DLFs than children with less hearing loss, but these relative differences in size of DLF would become smaller if the children with severe losses were given additional practice.

To investigate these notions two groups of children were tested. One was classified educationally as hard-of-hearing and the other as deaf. For comparative purposes, a smaller group of children with normal sensitivity was also tested.

B. Summary

In these experiments the following questions were asked:

Part I.

1. Is there a difference in threshold sensitivity when the stimulus is a continuous tone as

compared to an intermittent tone?

2. How much does the threshold of sensitivity change as the stimulus is shortened in steps from 250 to 10 msec?

Part II.

1. What is the size of the average difference limen for frequency in a group of severely hearing-impaired children?
2. Does the size of DLF decrease with practice?
3. In cases where DLF is large even after a small amount of practice, will size of DLF be reduced by further practice?
4. Is there a difference in size of DLF for conditions of fixed- versus variable-amplitude tones?
5. Is there a consistent relation between amount of hearing loss and size of DLF?

CHAPTER II

PART I. EFFECT OF DURATION OF SENSITIVITY

As previously mentioned, two aspects of the effect of duration on sensitivity were investigated. In the experimental and clinical literature, these topics are called threshold adaptation and temporal integration

A. Threshold Adaptation

1. Definition

Threshold adaptation, a diminution in sensitivity that results from sustained stimulation by sound, is measured in several ways (Carhart, 1957; Hood, 1950; Jerger, 1960). However, the basic measure is the difference in decibels between the just-audible amplitude of an interrupted sound and that of a sound delivered continuously for a specified time.

In the Carhart method (Tone Decay Test), after threshold is obtained for an interrupted tone, a continuous tone is delivered at threhold amplitude. Whenever the subject indicates he no longer hears the tone, with no interruption of signal, amplitude is increased 5 dB. The test ends when the tone remains audible for 60 seconds.

In the Hood method, after the threshold of a pulsed tone is obtained, the signal is continuously delivered 5 dB above threshold until the subject indicates the tone is no longer audible. The duration of audibility is recorded and the ear is rested for one minute. Tone amplitude is raised 5 dB and the test is repeated. The procedure is continued in increasing 5 dB steps until the tone remains audible for 60 seconds.

In the Békésy method (as described by Jerger [1960]) pulsed tones are delivered to the listener. The subject is required to press a switch whenever the tones are audible and to release the switch when the tones are inaudible. The switch controls a motor-driven attenuator which decreased signal voltage when the switch is pressed and increases voltage when it is released. The listener's responses are recorded by a pen attached to the attenuating mechanism which writes on a specially designed form. Ideally, this trace shows the range in signal intensity between just-audible and just-inaudible tones. After the threshold for the interrupted sound is recorded, a similar procedure is used with a continuously delivered tone.

2. Review of the Literature

a. Experiments with Normal-Hearing Adults

Threshold adaptation is rarely observed in subjects with normal sensitivity. Young adults show no more than 10 dB of adaptation (Sorenson, 1960) and the amount is usually 5 dB or less (Carhart, 1957; Hood, 1950; Jerger, 1960). With increasing age, slightly more adaptation is sometimes found, especially at higher frequencies (Schubert, 1944).

b. Experiments with Normal-Hearing Children

Children with either a chronological or mental age of seven years or more can do Bekesy audiometry (Price and Falck, 1963). However, children show higher thresholds by Békésy audiometry than by the conventional method, with younger children showing larger differences than older ones (Hartley & Siegenthaler, 1964).

c. Experiments with Hearing-Impaired Adults

Adults with impaired hearing show a variety of adaptation patterns ranging from no adaptation to eventual insensitivity even at the maximum output of the audiometer.

Carhart (1957) reported large variability in response patterns from a group of patients with sensori-neural losses. Few generalizations could be made about the pattern of responses obtained. Tone decay might occur at one frequency and not at another or be more severe at one frequency than at another. The duration of audibility is not systematically related to progressive increase in level above initial threshold. Tone decay is, however, more likely to occur at the higher test frequencies.

Sorenson (1960), using a modification of the Carhart method and a 2000 Hz test tone described three characteristic response patterns. The Type I pattern showed 10 dB or less tone decay and was considered to be the normal response pattern. The Type II pattern showed more than 10 dB decay during the first three minutes of testing, after which threshold remained fixed. The Type III pattern showed continuous tone decay, the test being terminated when the maximum output of the audiometer was reached.

Patients with retrocochlear diseases show more adaptation in general, than do patients with Menière's disease (Owens, 1964a). While in retrocochlear diseases, severe adaptation sometimes occurs even at frequencies where sensitivity is normal, in Menière's disease it rarely occurs below 2000 Hz if Hearing Level is less than 35 dB. In retrocochlear diseases, adaptation also occurs at a larger number of test frequencies and at a faster rate.

Jerger (1960), using the Békésy technique, classified the responses of 434 listeners with either normal or impaired hearing into four basic patterns. In the normal response pattern, the traces for the interrupted and continuous signals were interwoven. In the abnormal responses patterns (Types II, III, and IV) the threshold for the continuously delivered signal was at least 5 dB higher for some or all test frequencies.

Owens (1964b) questioned Jerger's classification by reporting that his data, obtained from patients with predominantly cochlear diseases, had to be separated into eight different response patterns.

The conclusion drawn from these studies is that adaptation, if present, is not always systematically related to frequency. Therefore, the relevant question for auditory training is, for a particular child, what frequencies are most likely to show adaptation and thereby might be associated with less stability of response?

Two recent studies have sought to determine how adaptation is affected by variations in a stimulus which initiates and then either maintains or fails to maintain the response to sound. Jerger and Jerger (1966) investigated how the listener's response to sound was affected by changes in the duration of the silent interval separating tones of 200 msec duration. They tested six listeners who did not maintain a stable threshold for continuous tones. Their listeners showed an approximately fixed maximum sensitivity when the silent interval was 200 msec or longer. At durations which ranged from 200 down to 40 msec, a critical off-time appeared. At the critical off-time sensitivity began to deteriorate rapidly, although a stable elevated threshold might still be obtained. For two of the listeners, further decreases in duration of the silent interval finally resulted in instability of threshold. For example, one listener showed a stable threshold at 15 dB sound pressure level (SPL) for 4000 Hz when off-time was 200 msec. He showed a stable threshold at 45 dB SPL with 100 msec off-time and a stable threshold at 60 dB SPL with 80 msec off-time. For off-times shorter than 50 msec, the signal rapidly became inaudible even at 110 dB SPL.

Dallos and Tillman (1966) reported similar results from the one subject they studied. This listener did not maintain a stable threshold even for signals as short as 25 msec if the off-time was 50 msec or less. Of further interest is the fact that, over a certain range of durations, threshold was not systematically related to on-time when off-time was fixed. The process is dependent on the duration of the silent period between stimuli rather than on the duration of stimulation.

Repeated measurements of individual subjects indicate that adaptation is reversible, at least in some instances. Adaptation can disappear with recovery from hearing loss accompanying mumps or peripheral neuritis. It may become more or less severe, depending on the severity of Menière's disease at the time of testing (Harbert and Young, 1962). Severe adaptation may disappear after successful remove of a cerebellar tumor (Jerger and Jerger, 1966).

Finally, Harbert and Young (1962) suggest that there are actually two types of adaptation. One type, called slow adaptation, is the type described above. Its time course is charted in seconds or minutes. The second type, called fast adaptation, is seen as a diminution in the width of the continuous-tone trace compared with the interrupted tone-trace. This can also be accompanied by a shift of 5 dB or less in the continuous-tone threshold. Its time course is in milliseconds and cannot be measured by conventional audiometry. They suggest that the two forms may occur concurrently. However, each is caused by the malfunction of different processes.

d. Experiments with Hearing-Impaired Children

The author was unable to find any descriptions of adaptation in hearing-impaired children. Whereas the hearing disorders of the adults who have been tested and which were discussed above were largely acquired after birth, the disorders of children are often congenital in origin. Whether these children would show similar adaptation is presently unknown. Harbert and Young (1964) suggest that cases of non-progressive congenital hearing disorders should not show adaptation because although many nerve fibers would be non-functional, those which remained would be normal. However they offered no data. Therefore, the relevance of adaptation to the development of stimuli for auditory training is unknown.

e. Summarizing this review

1. Threshold adaptation, defined as a shift in the pure-tone threshold in response to a continuous tone, is measured by any of three different methods, which are presumed to show the same process. Adaptation is possibly manifested in two ways: a shift in sensitivity for a continuous tone and a diminution in the width of the continuous-tone Békésy trace.
2. Threshold adaptation may be more or less severe and may be found at one or at many frequencies. Individual differences are large.

3. The stability or instability of a listener's response can depend on the duration for which the auditory system is allowed to rest between deliveries of tone.
4. The amount of adaptation that a person shows can change over time, depending on the course of the underlying disease.

3. Procedure Used in the Present Study of Threshold Adaptation

Subjects: The subjects were taken from the children enrolled in the upper grades at Central Institute for the Deaf. Forty-six boys and twenty-six girls were tested. The mean age of the group was 12.5 years. The range was 7 years and 9 months to 16 years and 10 months.

Test Ear: Test signals were delivered to one ear only. Usually the more sensitive ear was tested.

Test Room: The test room was a small classroom. The ambient noise levels, measured with a Bruel and Kjaer Sound Level Meter and Octave Band Filter, are given in Table I. The ambient noise would not affect the thresholds of the children tested.

No attempt was made to visually isolate the subject from the experimenter within the test room. Prior experience indicated that visual monitoring of the subject, along with reinforcing smiles or nods of encouragement, helped keep the subject's attention directed to the task. The subject was not, however, permitted to see the Békésy audiometer which

TABLE I

AVERAGE SOUND PRESSURE LEVELS OF OCTAVE BANDS OF AMBIENT NOISE RECORDED IN TEST ROOM

Center Frequency in Hz of Octave Band	Average Sound Pressure Level re 0.0002 dyne/cm^2
63	55
125	50
250	44
500	36
1000	36
2000	35
4000	28
8000	28

recorded his responses.

Apparatus: A diagram of the Békésy audiometer used to deliver the test signals and record the listener's responses is shown in Figure 1. The recording attenuator was a modified Model E5135c Grason Stadler Recording Attenuator.

Stimuli: The interrupted tones had a duration of 200 msec measured from the onset of the signal to the beginning of the offset and a rise and decay time of 10 msec. The silent interval between signals was also 200 msec.

The signal changed in frequency, beginning at 125 Hz and ending at 8000 Hz, during a 6-minute time period. Both the

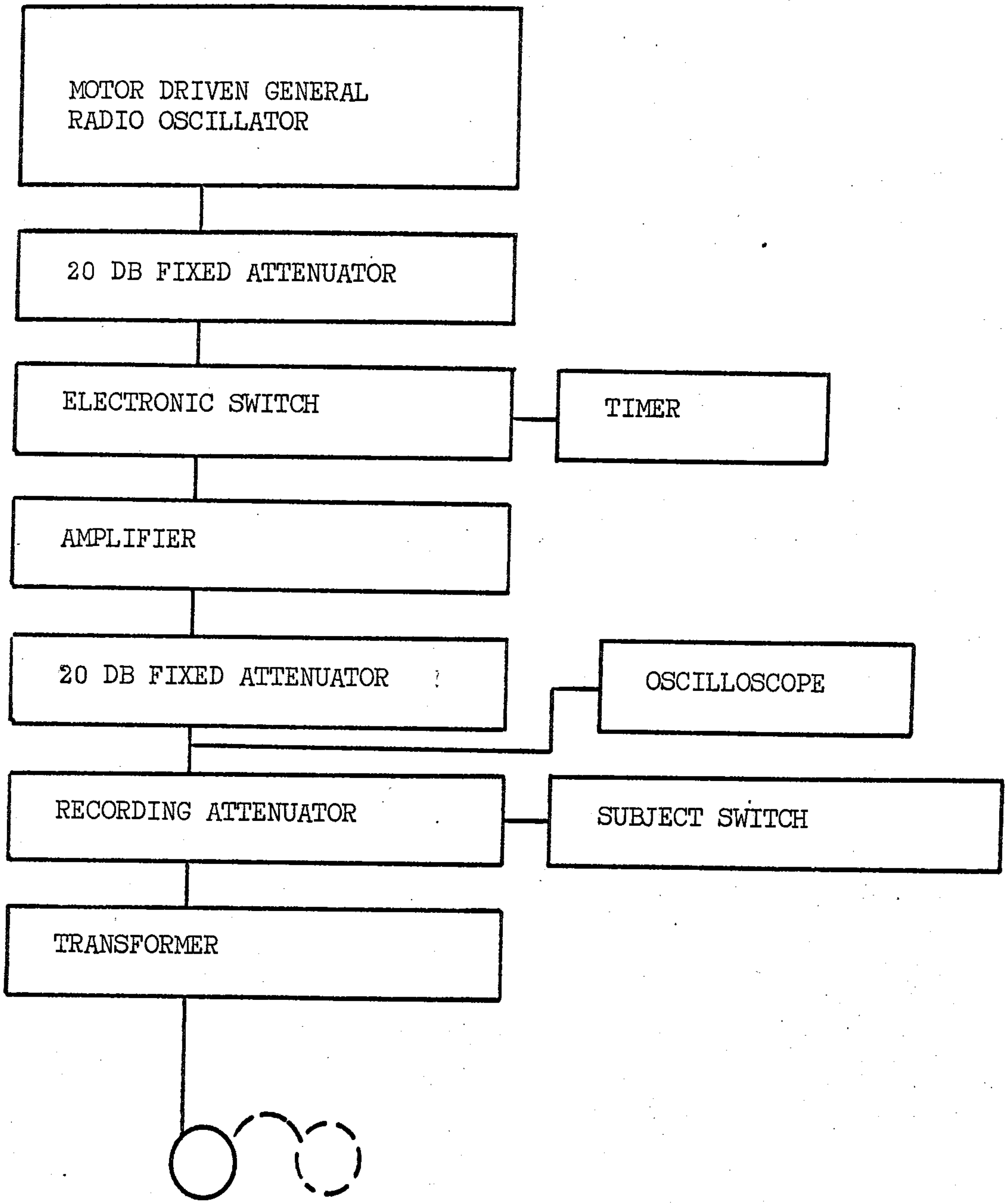


FIGURE 1. BLOCK DIAGRAM OF BEKESY AUDIOMETER USED IN PROBLEM I.

interrupted and continuously delivered signals were attenuated at the rate of 2 dB per second. The maximum intensities for the conventional audiometric frequencies are given in Table II. Sound pressure levels were measured in a 9-cc coupler with a Bruel and Kjaer Sound Level Meter and Octave Band Filter.

TABLE II

MAXIMUM OUTPUT OF AUDIOMETER AT THE CONVENTIONAL AUDIOMETRIC TEST FREQUENCIES

Frequency	Sound Pressure Level re 0.0002 dyne/cm^2
125	132 dB
250	132 dB
500	132 dB
1000	132 dB
2000	130 dB
4000	130 dB
8000	114 dB

Procedure: Adaptation was measured by the Békésy method. Listeners were always tested with the interrupted signal first, then with the continuous signal.

Before the test was begun, the experimenter (E) explained to the subject (S) that E wanted to test S's hearing. During the first test, S was instructed to listen for a "beeping" sound. Whenever S heard the beeps, he was to press the switch in the manner that E demonstrated. This would make the beeps go away. As soon as the beeps were gone, S was to release the switch. This would make the beeps come back. Through a combination of speech and gesture, E was usually able to instruct S that it was very important to press the switch as soon as he heard the beeps and to release the switch as soon as the beeps disappeared, and that he was to continue doing this for about 6 minutes.

The experimenter then delivered the signal fixed at 125 Hz and let S practice for a short period of time. After performance stabilized, the test was begun.

Similar instructions were given before delivery of the continuous tone. In this situation the sound was described as "going on all the time."

4. Results

A problem in Békésy audiometry is defining what point on the response trace to take as threshold. Whereas Harbert and Young suggest using the peak at which the subject begins to attenuate the signal voltage, other authors have used the mid-point of the pen excursion. A single criterion could not be employed in the present study for reasons given below.

1. Trace widths were not always stable within a condition. Some subjects produced traces which resembled amplitude-modulated wave envelopes. In other words, a subject might show several narrow

excursions and then a wide one. This suggested he occasionally needed a more intense sample of the signal, but when he received it, he allowed it to attenuate for a longer-than-usual period of time. These traces were analyzed by computing the difference between the mid-points of the two excursions.

2. The level at which the subject began attenuating might be uniform but the level at which he stopped attenuating would be variable. This suggested that the subject was more sure when he began detecting sound than when he stopped detecting it. Trace width varied randomly in this case. Therefore, the mid-point was greatly affected by changes in the subject's criterion for a just-inaudible sound. For these traces the levels at which attenuation began were taken as threshold.
3. The configuration of the trace was often different for the two stimulus modes. In such cases the experimenter chose the type of analysis which seemed best.

In all cases, differences were taken either between the mid-points of the continuous and the interrupted traces, or between the two corresponding peaks of the traces. The data were then grouped into 5 dB intervals, i.e., units comparable to those used in clinical audiometry. The results of the study are summarized in Table III. Results are not given above 3000 Hz because very little usable data were obtained above this frequency. For example, only 54 percent of the children gave measurable response at 4000 Hz.

The first row of Table III gives the number and equivalent percentage of children who showed less than 5 dB of adaptation, that is, less than 5 dB difference between continuous and interrupted thresholds. The second row gives the number of children who showed 5 dB or more adaptation. The third row gives the number of children who showed either no response or no scoreable response. This category indicates two types of response-failure: (1) trace excursions were limited by the maximum output of the audiometer for both continuous and interrupted tone and therefore threshold was not defined; (2) there was no response to the continuous tone, and peak values for the interrupted stimulus were less than 5 dB below maximum output. The second response is different from those in Row 1 in which the criterion for less than 5 dB adaptation was the difference in actual SPL for actual response to both types of stimulus. It is also different from those in Row 2 which includes cases where the differences between no response to a continuous tone and the SPL for response to an interrupted tone was greater than 5 dB. Finally, the fourth row gives the number of children who showed such erratic responses that they could not be included in the analysis. Two of these children had cerebral palsy and gave

TABLE III

NUMBER AND PERCENT OF CHILDREN SHOWING SPECIFIED KINDS OF ADAPTATION-RESPONSE

	250	500	1000	2000	3000	Hz
1.	49-68 %	44-61 %	32-44 %	14-19 %	12-17 %	
2.	7-10	13-18	22-29	32-44	33-46	
3.	5- 7	4- 6	7-10	15-21	16-22	
4.	11-15	11-15	11-15	11-15	11-15	
Total	72-100%	72-100%	72-100%	72-100%	72-100%	

1. Number and percent of Ss showing less than 5 dB adaptation.
2. Number and percent of Ss showing 5 dB or more adaptation.
3. Number and percent of Ss giving no scoreable response.
4. Number and percent of Ss giving erratic responses.

very slow motor responses in general. The remaining nine possibly did not understand the instructions.

The purpose of this table is to give a raw summary of the outcome of the use of Békésy audiometry with an unselected sample of deaf children. Row 4 shows that 15 percent of the sample could not do the task on the first attempt. Row 3 indicates some loss of data due to long response latency. Obviously if a child begins to attenuate a sound a second or two after the attenuator has stopped at maximum output he hears the sound. Actually, some data from Row 3 were usable for the purpose of this experiment. If these data are included with the data in Rows 1 and 2, then approximately 80 percent of the children tested gave useful data. Because the performance of the 11 erratic subjects cannot be evaluated, they are deleted from the analyses that follow. Therefore the size of the test sample is considered to be 61.

Table IV summarizes the results for this test sample. Rows 1 and 2 were described above. Row 3 shows the percentage of children who were previously described as showing less than 5 dB adaptation. Row 4 shows the percentage of children giving no scorable response.

TABLE IV

PERCENT OF CHILDREN SHOWING SPECIFIED AMOUNTS OF ADAPTATION

	250	500	1000	2000	3000
1.	80%	72%	52%	23%	20%
2.	11	21	36	52	56
3.	0	0	2	5	8
4.	8	7	10	20	18

1. Less than 5 dB adaptation.
2. Five dB or more adaptation.
3. Less than 5 dB measurable adaptation.
4. No scorable response.

The table indicates that adaptation is much more likely to occur above 1000 Hz than below. Slightly more than half of the children show adaptation at 2000 and 3000 Hz.

How much adaptation do the children show? Table V gives the number and percentage of children showing various amounts of adaptation. The percent is based on the number who actually showed adaptation and not on the total number in the sample. Note that for some children the absolute amount of adaptation is unknown because these children showed no response to the continuous tone at a particular frequency.

TABLE V

NUMBER AND PERCENT OF CHILDREN SHOWING SPECIFIED AMOUNTS OF ADAPTATION: ELABORATION OF TABLE IV

Adaptation in dB	250	500	1000	2000	3000
5- 9	2- 29%	8- 61%	14- 64%	13- 41%	9- 27%
10-14	1- 14	2- 15	6- 27	7- 22	5- 15
15-19	1- 14	1- 8	0- 0	2- 6	5- 15
<19	1- 14	0- 0	0- 0	1- 3	1- 3
<5	1- 14	1- 8	1- 5	6- 19	9- 27
<10	1- 14	1- 8	1- 5	3- 9	4- 12
Total	7-100%	13-100%	22-100%	32-100%	33-100%

The data from this experiment can also be looked at another way by simply asking, what percentage of the children failed to respond to continuous tones, to interrupted tones, or to both? This question is answered by Table VI.

TABLE VI

NUMBER AND PERCENT OF CHILDREN WHO FAILED TO RESPOND TO SPECIFIED TYPE OF SIMULUS

	250	500	1000	2000	3000
NR Continuous	1-2%	1-2%	3-5%	18-30%	18-30%
NR Interrupted	1-2	0-0	0-0	4- 6	4- 6
NR Both	1-2	0-0	0-0	4- 6	4- 6

This table shows that at 2000 and 3000 Hz 30 percent showed no res onse to continuous tones while only 6 percent gave no response to interrupted as well as to continuous tones.

The analysis given above describes the prevalence of slow adaptation. The data were also analyzed for the prevalence of fast adaptation. For purposes of analysis, fast adaptation is defined as a perceptable reduction in the width of the continuous trace compared to the interrupted trace. In most instances the continuous-trace width was half as wide as the width of the interrupted trace or less.

Thirteen of the 61 children who gave scorable responses, or 21 percent, showed this effect. Ten of these children also showed 5 dB or more slow adaptation at one or more frequencies.

5. Discussion and Conclusion

As part of the data analysis an attempt was made to classify the responses into the four categories of trace configuration described by Jerger. This would have been desirable in order to compare the incidence of the various types of trace for children who have hereditary or other congenital hearing disorders with adults who acquire hearing disorders later in life. Unfortunately, some of the present responses did not fit into any of Jerger's 1960 categories. Instead, they more nearly resembled the eight types that Owen (1964b) has described. Since test-retest reliability was not obtained in the present experiment, the validity of a meaningful categorization into so many types seemed questionable. Therefore, these data are not specifically compared with previous findings.

Since inspection of the traces gave no indication that the test population performed differently from any other population of hearing-impaired listeners, it is assumed that the subject's responses are valid indicators of adaptation. For frequencies below 1000 Hz most of the subjects showed either no adaptation or less than 10 dB. Above 1000 Hz relatively more subjects showed adaptation. However, of those who did, the majority still showed less than 10 dB adaptation.

These findings seem to warrant the conclusion that adaptation is not a significant factor which needs special consideration in the specification of signal durations in auditory training. For children with mild or moderate losses this conclusion is probably appropriate because these children retain a relatively large dynamic range between threshold and discomfort even after the ear has adapted. However, such a conclusion simply might not be true for such seriously impaired children as are found in a school for the deaf. A recent survey by Elliott (1967) indicated that approximately half of the children at Central Institute for the Deaf have thresholds of 105 dB SPL or greater for all audiometric frequencies between 125 and 3000 Hz. Also recall that the level of discomfort for hearing-impaired listeners is approximately 130 dB SPL. These findings indicate a dynamic range of 25 dB or less for half the children at CID. Furthermore, although modern hearing aids will deliver 130 dB SPL at one or more frequencies, it is sometimes difficult to teach a child to use his aid at this level, thus further reducing his dynamic range. For these children a 5-10 dB reduction in sensitivity could have a significant effect on the audibility and discriminability of incoming signals. This latter notion receives some support from the fact that 30 percent of the children tested did not respond to continuous tones at 2000 and 3000 Hz while only 6 percent responded to neither type of tone.

The results of the present experiment indicate a need for at least two further research projects. The first would ask the question: Assuming adaptation does occur, how rapidly does it take place? Obviously, if adaptation does not occur before a minute or more of steady-state tone delivery it is probably not an important consideration for development of stimuli to be used in auditory training.

Second, assuming adaptation does occur for pure tones, does it also occur for speech? As mentioned in the introduction, the speed signal is dynamic; that is, it is in a relatively continuous state of change. Whether the more or less rapid changes in amplitude and frequency, coupled with the silent intervals which occur at various times within the ongoing acoustic flow, are sufficient to mitigate or eliminate adaptation is unknown. It is known that persons with eighth-nerve tumors who show severe adaptation often also show little or no ability to discriminate speech. However, just how the speech signal is rendered indiscriminable by the underlying abnormality is not understood. Whether persons who show lesser amounts of adaptation show relatively less ability to discriminate speech than do listeners who show no adaptation has apparently not been reported. Therefore whether prior delivery of speech affects either the sensitivity or discriminability of ongoing speech is unknown. The present test group is known to show poor speech discrimination regardless of the presence or absence of adaptation. Nevertheless a relation between adaptation and discrimination cannot be completely discounted. Therefore adaptation and its relation to both the sensitivity and the discriminability of signals used in auditory training deserves further study.

B. Temporal Integration

1. Definition

Whereas adaptation refers to a shift in sensitivity in response to continuous stimulation, temporal integration refers to a shift in sensitivity when stimuli are made shorter than a critical duration. Specifically, for durations shorter than a critical duration, threshold intensity varies inversely with time. The rate of increase is approximately 9-10 dB for a tenfold shortening of duration. Thus for example, if duration is decreased from 100 msec to 10 msec, threshold intensity is increased 9-10 dB. This phenomenon is called temporal integration or temporal summation.

2. Review of the Literature

a. Experiment Done with Normal Listeners

Temporal integration has received considerable attention in recent years. Zwislocki (1960) and Olsen and Carhart (1966) give comprehensive bibliographies. Discussion in this section is limited to a general outline of the phenomenon as it is seen in listeners with normal sensitivity.

As previously mentioned, there is a critical duration at which the sound pressure level for audibility begins to increase. With further reduction in duration, threshold-level increases at an average rate of 9-10 dB per decade reduction in time. The critical duration can be longer than 500 msec (Olsen & Carhart, 1966), or as short as 100 msec (Harris, Haines & Myers, 1958). Average values of 150 msec (Miskolczy-Fodor, 1953) and 180 msec (Eisenberg, 1956) have been reported. Apparently, there is a wide variation in critical duration among listeners with normal sensitivity.

The average slope of the integration function for pure tones is 9-10 dB per decade of time. Miskolczy-Fodor (1953) reports a standard deviation of 2.4 dB for a 9 dB shift in threshold when a tone initially 100 msec long is changed to a 10-msec duration. Based on these data, a slope of from approximately 7 to 11 dB per decade of time would be common for individual listeners.

Some authors suggest the slope of the function relating time and intensity is frequency dependent (Garner, 1947) while others report no significant differences for different frequencies (Olsen & Carhart, 1966). Also, there might be a difference in slope for noise as opposed to pure tones (Garner, 1947). The issues remain unsettled.

Some of the differences in results are probably due to differences in method of obtaining the data and differences in the stimulus configuration (Olsen & Carhart, 1966). Some investigators used very fast rise times, which produced audible clicks at stimulus onset and offset while others used slower rise times. Also, signal duration has been specified in more than one way. Furthermore, because different listeners begin to show threshold shifts at different critical durations, averaging data increases the overall variability of group data (Green, Birdsall & Tanner, 1957).

b. Experiments Done with Hearing-Impaired Listeners

Miskolczy-Fodor (1953) attempted to use temporal integration data in the differential diagnosis of hearing disorders. He tested listeners with normal hearing, with conductive losses, or with sensori-neural losses with recruitment. (Recruitment is an abnormally rapid growth in the sensation of loudness as stimulus amplitude is progressively raised.)

The normal listeners and listeners with conductive losses showed very similar average shifts in sensitivity. The average slope of the function relating time to intensity increased 9 dB per decade, standard deviation was approximately 2.3 dB, and threshold began to shift at an average critical duration of 150 msec. In contrast, the group with sensori-neural losses and recruitment also showed a critical duration of 150 msec, but the slope of integration was only approximately 4.5 dB. The standard deviation was 2.9 dB.

Eisenberg (1956) extended the measurement of temporal integration to other categories of diagnosed hearing disorders. Her subjects were classified into the following categories: normal, diagnostically normal, conductive, fenestrated, mixed, and perceptive.

She found that deviations from normal temporal integration increased with degree of suspected neural involvement. Furthermore, both the percentage of subjects showing atypical temporal integration and the degree of deviation from normal increaed with test frequency. However, some listeners in each diagnostic category showed normal temporal integration.

Eisenberg also found a number of individuals who had normal sensitivity and normal speech discrimination but who showed atypical temporal integration. These atypical listeners constituted her diagnostically normal group.

Harris, Haines and Myers (1958) reported that the critical duration at which threshold intensity begins to change as a function of time varies greatly among subjects. While Miskolczy-Fodor and Eisenberg reported average critical durations of 150 and 180 msec respectively, Harris, Haines and Myers reported that in individual cases the critical duration is as short as 60 msec. Furthermore, a tenfold reduction in duration from this comparatively short critical duration might give either a normal or an atypical increase in intensity required for audibility.

In summary, these studies using hearing-impaired listeners show that: (1) in at least some types of hearing disorders the threshold for short duration tones is not raised to the same degree as it is in listeners with normal hearing; (2) the critical duration at which threshold begins to shift can be shorter than normal; and (3) there can be both an atypical critical duration and an atypical integration function or either one of these two phenomenon. No reports have suggested that the audibility of short duration tones is relatively poorer in hearing-impaired listeners than in normal listeners.

No data are available about the slope of the temporal integration function for children with hereditary or other congenital hearing losses. Therefore, the effect of short-duration stimuli on sensitivity is not known for such children and as a consequence, the relative importance of short durations for the detectability of stimuli used for auditory training is unknown.

3. Procedure Used in the Present Study

Subjects: The same subjects used in the adaptation experiment were tested in this experiment. However, only 56 subjects completed this test.

Apparatus: The audiometer used in this experiment is the same as that used in the adaptation study (see Figure 1). However, MX-41/AR cushions were substituted for the M-301 cushions. This change was made for the following reason. The results coming in from the adaptation study showed that in some cases the difference between the subject's threshold and the maximum output of the audiometer was less than 20 dB. Without this 20 dB range, there was the possibility of not being able to obtain the threshold for all four durations of signal delivered in the present study. Data were available which suggested that less voltage was required to produce an audible sound when MX-41/AR cushions were worn than when M-301 cushions were worn (Jerger & Tillman, 1959). Therefore, the change in cushions was made.

Stimuli: Test signal frequencies were 500 and 1000 Hz. Signal durations were 250, 100, 25, and 10 msec. Duration was measured from onset of signal to onset of decay. Rise and decay time was 5 msec. Signals were delivered twice per second.

Procedure: The subject's task was essentially the same as in the adaptation experiment and therefore he was given similar instructions.

The test was begun by delivering signals with a duration of 250 msec. After performance had stabilized, the paper drive on the attenuator was turned on. At intervals of approximately 1.5 minutes, the duration of the signal was decreased first to 100 msec, then to 25 msec, and finally to 10 msec.

Some subjects were tested with the 500 Hz tone first; others were tested with the 1000 Hz tone first. The same ear that was tested in the previous experiment was used for this test.

4. Results of the Present Study

Inspection of the Békésy tracings produced by the subjects indicated that the peaks at which they began to attenuate the audible sound gave the most reliable estimate of performance. Recall that the subject responded for 1.5 minutes to each duration. The first 0.375 minute of responses was considered practice and these data were discarded. During the remaining 1.125 minutes subjects typically produced four to eight peaks in the trace. The value of each peak to the nearest 0.5 dB SPL was recorded. These data were then averaged for each subject.

Next, the difference in threshold between the 250 msec duration and each of the three shorter durations was computed. For each subject, four scores were recorded for each frequency; the fourth being zero. (The average level for the 250 msec duration subtracted from itself.) Since the average level increased as duration decreased, the algebraic sign of the difference scores was reversed. The data were then averaged across subjects.

Of the original 72 subjects given the adaptation test only 58 subjects gave usable data in this experiment. For 10 of the remaining subjects, pen excursions at both frequencies were too variable to score. Four of the subject's responses were limited by the maximum output of the audiometer at one or more durations. Two of the 58 gave scorable data only at 500 Hz; two gave data only at 1000 Hz. For the correlation analyses reported later in this section the only data used are from the 54 subjects who responded at both frequencies.

The average differences in threshold as a function of stimulus duration and the corresponding standard deviations are given below.

TABLE VII

AVERAGE THRESHOLD SHIFT IN dB FOR SPECIFIED DURATIONS OF TONE AND ASSOCIATED STANDARD DEVIATIONS

Frequency		Duration 250	100	25	10
500	$\overline{X}$	0.00	1.39	4.34	6.45
	SD	0.00	1.26	2.08	2.52
1000	$\overline{X}$	0.00	0.88	2.99	5.15
	SD	0.00	1.21	1.47	2.08

Inspection of the average differences indicates that the slope of the integration function is less than 9 dB per decade. The relation between duration and intensity is better seen in Figure 2. The broken line, representative of the performance of normal listeners, is taken from Miskolczy-Fodor.

The data from the present experiment are shown by the two lower lines. It can be seen that the slope of the functions are shallower for the hearing-impaired children than

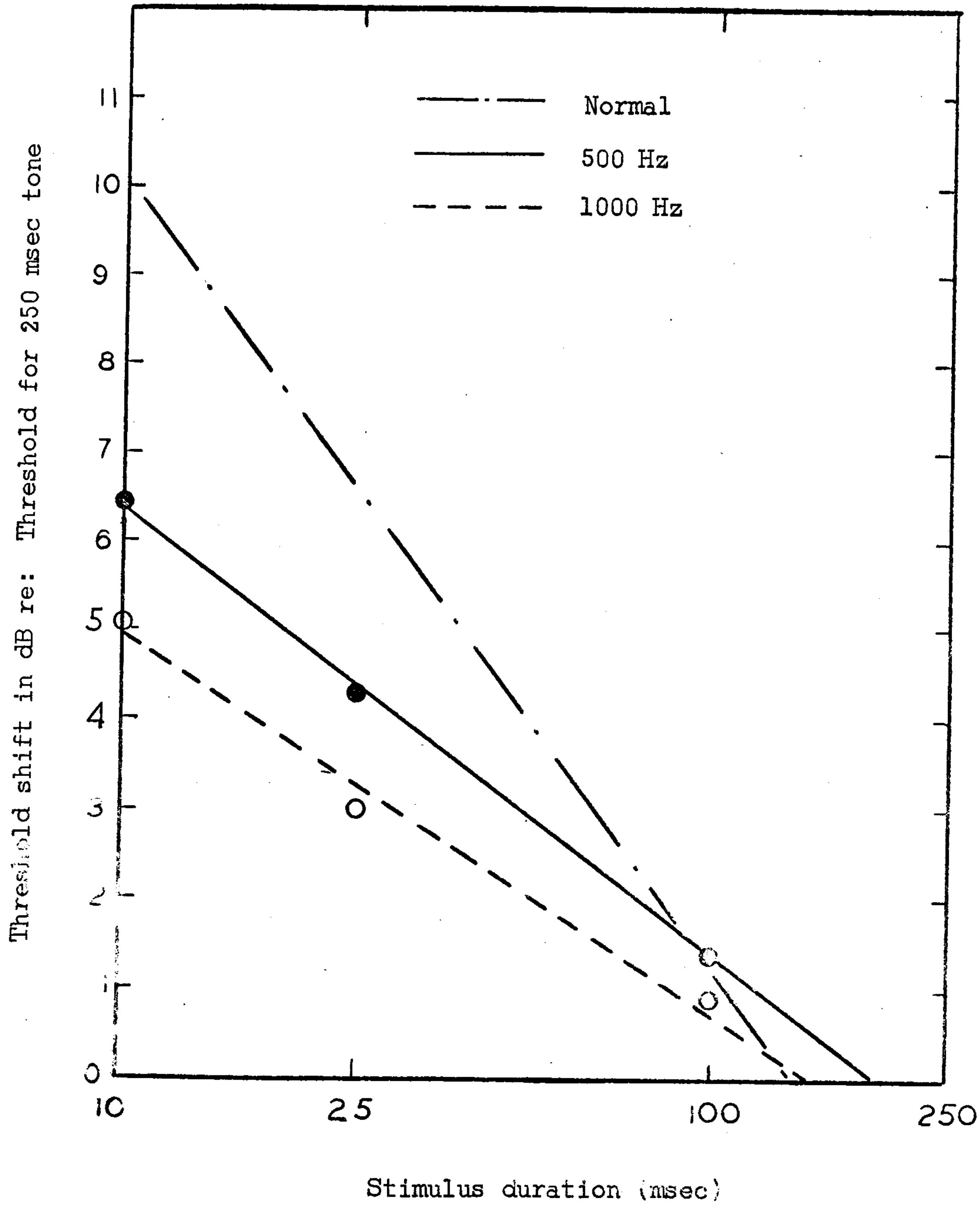


FIGURE ... ...E THRESHOLD SHIFT AS A FUNC... ... ...S
...TION.

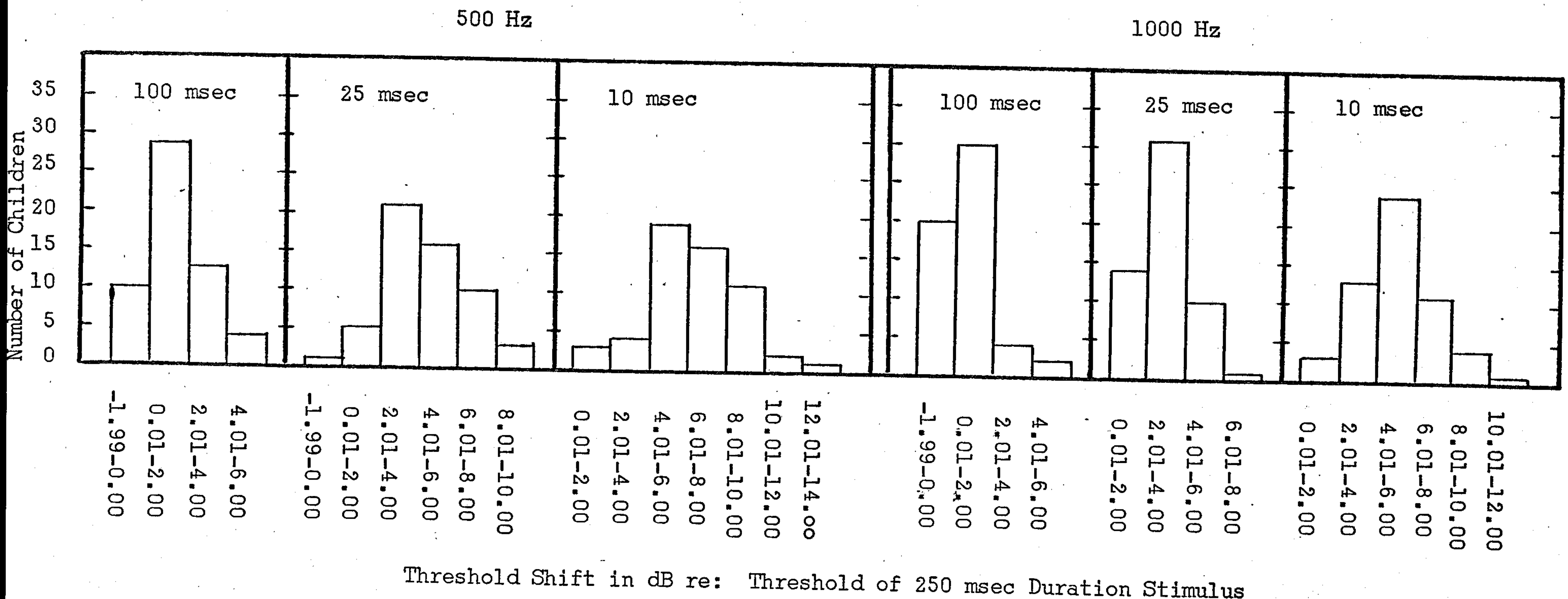
for the normal listeners. This means that the rate at which threshold is shifted by changes in duration is slower for the hearing-impaired children than for the normal listeners. In addition, the absolute amount of threshold shift as a function of duration is less for the test group than for normal listeners.

In order to specify some minimum duration of stimulation an important question is: What is the distribution of shift in threshold as duration is successively decreased? In other words, what proportion of children show a specified shift in threshold as duration is cut to a specified value? The distributions of differences in threshold between 250 msec and the successively shorter durations are given in the panels below.

The distributions for the 500 Hz test will be discussed first. As would be expected, the distribution of each duration is skewed to the right. This would be expected since it is assumed that threshold would shift upward as duration is shortened.

It can be seen that 10 subjects actually had lower thresholds for the 100 msec signals than for the 250 msec signals. This finding is difficult to explain since it is assumed that listeners could have the same thresholds at the same two durations (Harris, Haines & Myers, 1958) but not a lower threshold at 100 msec. Possibly this finding reflects the within-subject variability of steady state thresholds.

FIGURE 3. DISTRIBUTIONS OF THRESHOLD SHIFT FOR SPECIFIED STIMULUS CONDITIONS.



However, this assumption could only be checked by obtaining repeated measurements on the same subjects. The standard deviation of 1.1 around a mean of 1.4 which Miscolczy-Fodor reports indicates that some of his hearing-impaired adults also gave lower thresholds at 100 msec than at 300 msec.

Further inspection of the histograms show that when duration was shortened to 100 msec no subject showed a threshold shift of more than 6 dB. When duration was further shortened to 25 msec 24 percent of the subjects showed more than 6 dB shift in threshold. Finally, when duration was shortened to 10 msec, 56 percent showed more than 6 dB shift in threshold.

The same general trends appear in the data gathered at 1000 Hz. However, it is evident that the subjects showed less threshold shift than at 500 Hz. This is reflected by the smaller mean values and also by a smaller range of scores. No subjects showed more than 6 dB shift when duration was shortened to 100 msec and at 25 msec only one subject showed more than 6 dB shift. Thirty percent showed more than 6 dB shift when duration was shortened to 10 msec.

Both the mean values and the distribution of scores suggest that performance was different for the two frequencies; that is, there was less threshold shift for the 1000 Hz signal than for the 500 Hz signal. A series of t tests were performed to test the null hypothesis of no difference as a function on frequency. The difference scores and associated values of t are given below.

TABLE VIII

AVERAGE DIFFERENCE IN THRESHOLD SHIFT BETWEEN 500 AND 1000 Hz TEST TONES AND ASSOCIATED VALUE OF *t*

	100	25	10	msec
D =	0.51	1.35	1.30	
t =	2.55	4.22	3.17	

The probability of obtaining a value of *t* as large as 2.55 by chance is less than 0.02. The probability of obtaining a value as large as 3.17 or larger is less than 0.01. The null hypothesis is therefore rejected.

This finding is somewhat unexpected since both Miscolczy-Fodor (1953) and Eisenberg (1956) assumed no difference in threshold shift as a function of frequency. Support for the present finding is however found in data published by Elliott (1963). She found differences in slope as a function of frequency. The higher the frequency the shallower the slope. The present data show similar trends. However, two alternative trends might underly the data.

Since the differences for durations of 25 and 10 msec are very similar, these data would support the notion that the slopes of the functions are parallel and therefore have a different axis crossing. The implication of this notion is that the critical duration at which temporal integration begins to occur, changes with frequency. For the present data, the critical duration is smaller at 1000 Hz than at 500 Hz. Harris, Haines and Myers (1958) also reported different critical durations at different frequencies. However, they did not mention any systematic trends in their data.

An alternative possibility is that the difference in slope is a real difference. Elliott's suggestion that slope varied with frequency was based on computations of slope determined by fitting a line to the data obtained at 10 msec duration and at 100 msec duration. As Figure 3 shows, a visual line of best fit of the data obtained in the present experiment indicates that the slopes are different and that there is only approximately 15 msec difference in critical duration between the two frequencies. If it is assumed that critical duration is the same at both frequencies, then the average critical duration is approximately 178 msec. This value is in close agreement with the 180 msec value that Eisenberg reported.

Inspection of the distributions of threshold shift for 100 msec durations is useful in deciding which notion is more plausible. In Figure 3 it can be seen that 19 percent of the listeners showed either lower or the same threshold for durations of 250 and 100 msec when test frequency was 500 Hz. When test frequency was 1000 Hz, 37 percent of the subjects showed no positive shift in threshold. As was mentioned before, this might simply reflect subjects' unreliability of performance. Were this later notion rejected, then the present data support the hypothesis that there is a difference in critical duration between the two frequencies.

One measure of the consistency of the subjects' performance is the correlation between threshold shift at 500 Hz and at 1000 Hz for the same duration. A high correlation would indicate that the subjects' performance was reliable. It would also indicate that the hearing disorder which underlies atypical temporal integration had systematic effects at different frequencies. On the other hand, if the correlation were low, it could indicate either subject unreliability, or independence of temporal integration as a function of frequency, or both. The correlation between the threshold shifts at the two frequencies for 10 msec signals was 0.16. It is concluded that, for individual subjects, performance is independent of test frequency. This conclusion is indirectly supported by the findings of Harris, Haines and Myers. They did not report correlations between frequencies, but inspection of the individual cases they reported indicates that for a particular subject both the critical duration and the slope of integration are independent of frequency.

Harris, Haines, and Myers further reported that there was no systematic relation between the degree of atypical temporal integration and the results of other auditory tests, thereby concluding that a test of temporal integration gave additional information as to the locus of the hearing disorder. In agreement with this conclusion is the present finding that a number of the hearing-impaired children tested in the present experiment showed normal temporal integration.

Correlation analysis between threshold in SPL for 250 msec tones and threshold shift for 10 msec tones yielded a Pearson $\underline{r}$ of -0.33 at 500 Hz and -0.19 at 1000 Hz thereby indicating little correlation between Hearing Level and temporal integration. These results disagree with the data reported by Elliott (1963) that are given below.

$\underline{r}$ =	500	1000	4000	Hz
	-0.41	-0.51	-0.85	

Possibly, if the test group is homogeneous according to hearing disorder, for example, noise-induced trauma, the two variables are related to the degree Elliott reports.

Finally, Harris, Haines, and Myer's finding of no systematic relation between adaptation and temporal integration is confirmed by the present data. The correlation between amount of adaptation and amount of threshold shift for a 500 Hz tone of 10 msec duration was 0.04. Inspection of the data for the 1000 Hz tone indicated that a similarly low correlation would be found.

5. Discussion and Conclusions

It is evident that, on the average, the threshold of severely hearing-impaired children is shifted less by shortening the duration of the test tones than is the threshold of normal listeners. However, any variation in the stimulus which makes it less likely to be heard affects the severely impaired listener more than it affects a listener with a mild or moderate loss because the severely impaired listener has only a small dynamic range of audibility to begin with. Therefore regardless of whether a severely impaired listener shows normal or atypical temporal integration, the effects of duration on sensitivity should be considered when developing stimuli for auditory training.

The effect of atypical temporal integration on sensitivity can be interpreted in two ways depending on the duration used as a reference point. In routine clinical audiometry, stimuli longer than 200 msec are normally used to measure threshold. When this threshold is used as a reference point, atypical temporal integration might be interpreted as being a fortunate circumstance because a child who shows such behavior has a wider dynamic range as a function of duration than does a child who shows normal integration. Since he shows less threshold shift as a function of duration he is more likely to detect the presence of the transient signals which comprise speech. In this sense, an atypical shift of 5 dB rather than a typical shift of 10 dB would be an asset to a child's ability to detect the presence of sound.

On the other hand, if the threshold for a tone of very short duration is taken as the reference point, then atypical temporal integration is not an asset. In this case, the child with a normal integration function has a lower threshold for long duration tones and therefore a wider dynamic range than a child who shows atypical temporal integration. Since many of the phonemes that comprise speech are shorter than the normal critical duration of 150 to 180 msec, a more realistic estimate of threshold in terms of the audibility of phonemes might be obtained by measuring thresholds with signals of perhaps 40 msec duration.

Regardless of the reference point taken, atypical temporal integration indicates another impairment of deaf children. It is plausible then in some hearing disorders very rapid adaptation occurs. In such instances the child could not benefit from sustained stimulation to the extent that other children do. If very rapid adaptation is assumed, then a shortened critical duration reflects the time required to completely adapt the nerve fibers. This assumption would account for the shortened critical duration reported by Harris, Haines and Myers (1958) and the suggestion of shortened critical duration seen in some of the present data.

This explanation does not account for children who show a slope of temporal integration which is less steep than normal. One might assume that in some hearing disorders there is a relatively smaller and less dense neuronal population than in other hearing disorders. In these cases the increase in neural excitation from spacial spread of physical excitation due to increase in the amplitude of the signal would be less than in the normal ear.

Therefore, the effect of spacial summation on temporal summation would be reflected by a function that is less steep than normal. Of course, this type of disorder could occur concurrently with very rapid adaptation and produce both a shortened critical duration and a shallow temporal integration function.

These notions are also consistent with the data from the present adaptation experiment. Notice that although the interrupted tone is only 200 msec long, its actual duration of audibility could be governed by the critical duration and therefore could easily be less than 200 msec. Therefore, in cases of very rapid adaptation, there would be no difference between interrupted and continuous thresholds. On the other hand, if the rate at which adaptation occurs is relatively slow, then a difference between interrupted and continuous thresholds would be seen. These differences in rate of presumed adaptation might reflect disorders which are different in kind or only in degree.

At present it is not known if or how the disorders affecting temporal integration affect the discrimination of speech and other materials used in auditory training. However, the present experiment suggests that a slow rate of speaking would increase the likelihood for detecting the phonemic elements of speech and therefore might make speech more discriminable.

Both duration-experiments point out that there are individual differences in response to the duration of a sound. Amplification does not necessarily provide the child with a "normal" signal. These experiments suggest the need for careful study of how signals are distorted by hearing disorders and how, in the face of this distortion, the maximum possible information can be delivered for interpretation by the listener.

CHAPTER III

FREQUENCY DISCRIMINATION

A. Definition

A basic problem in sensory psychology is: What is the relation between a physical stimulus activating a particular sensory system and the resulting sensation? In the present experiment, the physical variable is the frequency of a tone delivered to a listener, while the psychological variable is called pitch. When two tones of different frequency are alternately delivered, the listener may or may not report that they are different in pitch. If he consistently reports differences, it can be inferred that he can discriminate between them.

One author (Harris, 1952a) has chosen to call ability to recognize differences in frequency, "pitch discrimination." Another (Hirsh, 1952) has chosen the term, "frequency discrimination." Whereas normal listeners probably have an intuitive understanding of the meaning of pitch, whether the sensation of pitch is the same in hearing-impaired listeners is not known in each individual case. To avoid the possibility of making erroneous inferences about the sensations occurring within hearing-impaired listeners, the term frequency discrimination will be used in this study.

Knowing that a listener can discriminate some frequencies from others indicates that all frequencies do not sound alike to him. However, if, for example, we expect to teach a hearing-impaired child to make fine discriminations, an important question is: What are the limits of his ability to discriminate differences in frequency? Said another way, what is the smallest difference in frequency that he can recognize?

The minimum difference in frequency that can be discriminated is herein called the difference limen for frequency (DLF). As will be seen in the review that follows, the difference limen for frequency (DLF) is dependent on the listener, the stimulus, and the method of measurement. Thus, a specific definition of DLF entails specifications of all these factors.

B. Review of the Literature

The ability of normal listeners to discriminate differences in frequency has been studied for over a century and therefore considerable information is available about a number of factors that influence performance. Since the same factors can be assumed to influence the performance of hearing-impaired listeners, this literature is summarized before the literature dealing with hearing-impaired listeners is reviewed. The three general factors that influence the size of DLF, namely; (1) the listener, (2) the stimulus, and (3) the method of measurement, are discussed below.

1. <u>The Listener</u>

a. Practice Effects

Comparison of data obtained from highly trained listeners (Delezenne, 1827; Harris, 1952a; Koester, 1945; Luft, 1888; Meyer, 1898; Stucker, 1908) with untrained listeners (Stücker, 1908; Harris, 1952; Shutts, 1950) shows that trained listeners give smaller DLFs. This effect is clearly seen in data given below which show the size of DLF for both trained and untrained subjects tested by the same method (Harris, 1952a).

TABLE IX

DLF AS A FUNCTION OF FREQUENCY FOR TRAINED AND UNTRAINED SUBJECTS

	125	250	500	1000	2000	4000	Hz
Trained	.51	.97	1.18	1.70	4.00	10.78	Hz
Untrained	.74	1.33	2.09	3.61	8.28	21.09	Hz

Wyatt (1945) after reviewing the early work on effects of practice and training on ability to discriminate frequency differences criticized many of the reports that showed no improvement in performance on the grounds that (1) subjects were initially at a high level of performance and therefore could not greatly improve; (2) inappropriate handling of the data may have concealed improvement in performance; (3) subjects may not have been properly motivated or did not properly understand how best to do the task. She noted that where intensive remedial training had been given to subjects who initially showed poor ability to discriminate differences in frequency, performance did improve.

To demonstrate her thesis Wyatt (1945) gave twelve 50 minute periods of individual training in both pitch intonation and frequency discrimination to 16 subjects who initially showed large DLFs. Her subjects not only showed significant improvement in performance for the training frequency of 500 Hz but also for 250 and 1000 Hz.

b. Individual Differences

As with most other skills individual differences are found even when practice effects are taken into account. This is quite evident in the data given below which shows that the DLFs for two highly trained listeners differ by a factor of three (Rosenblith & Stevens, 1953).

TABLE X

COMPARISON OF DLF FOR TWO HIGHLY TRAINED LISTENERS

	250	1000	4000	Hz
KNS	.34	1.2	8.7	
WAR	1.4	3.5	23	

c. Maturity

On the average, children show larger DLFs than do young adults (Bradley, 1959; DiCarlo, 1962; Houchins, 1962; Riach, 1967; Seashore, 1910). This difference reflects a practice effect and is not due to physiological development. Seashore (1910) makes the following conclusions about differences due to age:

1. In a bright child with a good ear the physiological limit can be established for all practical purposes as early as the age of five.
2. The slight inferiority of record which we find in a group of young children over the record of a group of adults is due to cognitive difficulties, which are not in the nature of a lack of skill in the sense of a slowly acquired ability but rather due to lack of knowledge. The university students have every advantage--musical education, maturity for reliability in observation, power of application, familiarity with the experimental conditions, etc. which is quite enough to account for the superiority of their group record over the record of a group of children.

Median values reported by various authors are summarized below. Inspection of the data indicates that the medians are about twice the size of the median DLF for untrained adults, but that there is considerable overlap between the distributions of scores from adults and children.

TABLE XI

REPORTED MEDIAN DLFs FOR CHILDREN WITH NORMAL SENSITIVITY

	250	500	1000	2000	Hz
Bradley		6.8	7.4	8.9	
DiCarlo		3.7	7.0	10.8	
Houchins	4.5		8.0	13.5	
Riach			8.2		

2. <u>The Stimulus</u>

Two fundamentally different types of stimuli have been used in measuring DLF. In one type frequency is changed during a silent interval which separates pure tones of different frequency. Since the listener compares the second tone with his memory of the first tone, this DLF is called the DLF for frequency memory (Harris, 1952). In the second type the frequency periodically changes without being interrupted. The DLF measured with this stimulus is called the DLF for frequency modulation.

When the same subjects are tested by both methods there is no correlation between performance, thereby indicating that two independent abilities are measured when the two stimuli are used (O'Hare, <u>et al</u>., 1959). Harris (1952a) suggests that the frequency modulation technique measures the ability to discriminate beats or is some kind of masking experiment. Nevertheless the frequency modulation technique has been used in testing hearing-impaired listeners and therefore results using this method will be reviewed as well as results using the frequency-memory technique.

DLF for Frequency-Memory

1. Effects of frequency. The absolute size of DLF increases with frequency. Whereas the DLF might be less than one Hz at 125 Hz (Harris, 1952a; Saslow, 1967) it can be as large as 300 Hz at 10 KHz (Henning, 1966).

2. Effects of intensity. The absolute size of DLF first decreases as level above threshold is increased and then remains fixed for further increases in level. The loudness level at which the minimum DLF is achieved increases with frequency. However for test frequencies below 2000 Hz the differences between levels of 15 and 25 dB are less than one Hz (Harris, 1952a). When intensity is expressed as Sensation Level, minimum DLF is achieved at 25 dBSL at 500 Hz but not at 1000 Hz or above (Shutts, 1950).
3. Effects of stimulus duration. Because of methodological differences between studies, generalizations about the effect of duration remains tenuous. Nevertheless, the smallest DLFs are apparently obtained when the stimulus duration is between 0.8 and 1.6 seconds (König, 1957). However, the difference in DLF for durations of 0.4 and 0.8 seconds is less than 0.5 Hz. According to Chin-an and Christovich (1960), DLF is relatively fixed until a critical duration of approximately 158 msec is reached. For shorter durations there is a systematic increase in size of DLF as duration is progressively shortened. As might be expected the size of DLF for tones of short duration is also affected by the Sensation Level at which they are delivered. The rate of increase in size of DLF with decrease in Sensation Level is

faster for a tone of 35 msec duration than for one with a 100 msec duration (Turnbull, 1944).

4. Effects of interstimulus interval. The effect of interstimulus interval on size of DLF is different for a fixed-standard method of stimulus presentation (the standard always precedes the comparison tone), than for a roving-standard method of presentation (either the standard or comparison tone is delivered first) (Harris, 1952b; König, 1954). Whereas in the fixed-standard method, increase in the size of DLF is less than one Hz when interstimulus interval is increased from 0.3 to 15 second, DLF increases rapidly when the interstimulus interval is greater than one second in the roving standard method (Harris, 1952b).

5. Interaction between Intensity and Frequency. Early investigators indicated that the relative intensity of a signal affected its perceived pitch. The data indicated that the pitch of low frequencies decreased with increase in intensity, the pitch of high frequencies increased, and the pitch of mid-frequencies remained unchanged as intensity increased (Snow, 1936; Stevens, 1935). However, a recent study indicates that for the two to 10 dB differences in amplitude employed in the present study, pitch shifts would be unlikely (Cohen, 1961).

A second type of interaction occurs for high frequency test signals, where the DLF is relatively large and the threshold of audibility is rising rapidly. Here it is possible that the lower of two frequencies, although delivered at the same intensity, is perceived as being louder and therefore judgment is mediated by a loudness cue. A recent experiment indicates that for frequencies above 3000 Hz the DLF is much larger when variable amplitude differences exist between the standard and comparison tone than when both tones have the same amplitude (Henning, 1966).

3. <u>The Effects of Method of Frequency-Memory DLF</u>

a. The Method of Limits

In this method, also called the method of minimal change, differences in frequency which are easily discriminated by the listener are gradually reduced by the experimenter until the listener reports he can no longer discriminate a difference between the standard and comparison tone. This Δf is recorded while the experimenter continues changing the frequency of the comparison tone until the listener reports he again discriminates a difference. By averaging a number of Δfs for "just same" and "just different" an estimate of DLF is obtained. Variations of this method have been employed since 1888 (Luft, 1888; Stücker, 1907; Bradley, 1959).

b. The Method of Constant Stimuli

In this method, also called the method of right and wrong cases, and the AX method, a series of fixed differences in frequency are delivered. The listener can be required to respond in one of several ways. For example, his response could be either "same" or "different." Alternatively response could be "second tone higher" (or lower or same). In yet another variation, the ABX method, the listener is given three tones. The first two are different in frequency. The listener must judge whether the third tone is the same as the first or second one. In all cases, the DLF is estimated by plotting percent correct as a function of Δf and taking the Δf associated with 75 percent correct. The method of constant stimuli has been used since 1898 (Meyer, 1898; Koester, 1945; Shutts, 1950; Harris, 1952a; Turnbull, Chin-an & Christovich, 1960; Konig, 1957; Henning, 1966).

c. Comparison of the Two General Methods

According to Boring the two methods do not yield comparable DLFs. The method of limits measures, in part, the average spread of the equal category. The listener's criterion for "same" and "different" will affect the size of DLF. In the method of constant stimuli, variability of the sensory system in response to the stimuli will partly determine the size of DLF (Boring, 1940).

d. Other Consideration Involving Method

Smaller DLFs are obtained when the "same-different" response is used than when a judgment of direction of frequency-difference is required (Knudsen, 1923). Repeated presentations of stimuli favor smaller DLs than single presentations (Hirsh, 1959). Controversy remains whether the AX method yields smaller DLFs than the ABX method (Rosenblith & Stevens, 1953; Saslow, 1967). Sixteen variations in method yielded differences in size of DLF as large as 26 Hz at 800 Hz (Harris, 1948). Feedback, that is, immediate knowledge of correctness of response, affects performance, but not in easily predicted ways (Campbell & Small, 1963).

Rosenblith and Stevens (1953) offer some incidental observations and speculations which further elucidate the problem of measuring ability to discriminate differences in frequency.

1. The ability to discriminate frequency-differences is probably dependent on the size of the set of different alternative frequencies which may follow the first tone in a pair. If the set of alternatives is small, discrimination will be better.
2. The difficulty of the test as a whole influences performance. Performance is better if the listener is given some "easy" pairs to discriminate which he knows are correctly identified.
3. More information on the listener's performance could be obtained by, for example, asking him to rate his confidence about how correct he is, or measuring the latency of his responses.

DLF for Frequency-Modulation

1. Effects of frequency. Contrary to the classic data of Shower and Biddulph (1931), a number of authors report a progressive decrease in size of

DLF as frequency is decreased (Knudsen, 1923; Young, 1926; Meurman, 1954; Filling, 1958). According to Shower and Biddulph the absolute DLF is approximately constant between 62 and 500 Hz.

2. Interaction between frequency and rate of change in frequency. For frequencies below 1000 Hz smaller DLFs are obtained when frequency is changed abruptly than when it is changed slowly (Knudsen, 1923; Young, 1926; Shower & Biddulph, 1931). This might be due to the presence of transients associated with abrupt changes in frequency (Shower & Biddulph, 1931) or to a contour effect (Boring, 1940).

3. Effects of intensity. Increases in Sensation Level initially decrease the size of DLF but when level is increased beyond 20 to 40 dBSL intensity has no further effect (Shower & Biddulph, 1931). No systematic relation between frequency and level associated with minimum DLF is evident (Shower & Biddulph, 1931).

4. Effects of modulation rate. The smallest values of DLF are obtained with modulation rates of about two per second. (Shower & Biddulph, 1931; Filling, 1958; Schecter, 1949). For rates between 4 and 75 Hz, DLF is very nearly proportional to the square root of the modulation rate (Schecter, 1949).

5. Effects of method. The method of limits has been used by most authors (Knudsen, 1923; Young, 1926; Shower & Biddulph, 1931; Meurman, 1954; Filling, 1958). After evaluating the method of adjustment, the method of constant stimuli, and the method of limits Schecter (1949) concluded that comparable and reliable data could be obtained with either the method of adjustment or the method of constant stimuli. In contrast, data obtained by the method of limits did not agree with data obtained by either of the other two methods. Some listeners relied on a time cue in changing from a "same" to a "different" response. For others, the perception of modulation built up slowly, and the listener only became aware of it after the modulation was quite discriminable. Were he allowed to reverse direction at this point he could continue to perceive modulation down to a smaller Δf.

4. <u>Frequency-Modulation Studies with Hearing-Impaired Listeners</u>

Attempts to use the DLF for frequency modulation to assist in the differential diagnosis of hearing disorder have not been successful because the distribution of scores within any one diagnostic category overlap with scores within other categories. Meurman (1954) concluded that: (1) DLF is essentially the same for listeners with normal hearing and listeners with conductive impairments; (2) listeners with sensori-neural disorders, especially Menière's disease, often show DLFs that are larger than normal; (3) some listeners while showing normal sensitivity at a particular frequency show abnormally large DLFs, and (4) an abnormally large DLF differentiates a sensori-neural from a conductive disorder.

Filling (1958) reported that whereas in listeners who show recruitment the DLF is two or more times larger at 5 dB Sensation Level than at 20 dBSL, listeners who show no recruitment do not show such large differences in DLF at the two Sensation Levels. However, apparently not all listeners with recruitment have abnormally large DLFs (Harris, Haines & Myers, 1955).

5. <u>Frequency Memory Studies with Hearing-Impaired Listeners</u>

Since a frequency-memory DLF was studied in the present experiment, previous investigations of this type of DLF with hearing-impaired listeners are given in greater detail. Specific details of studies with hearing-impaired children follow the general findings.

1. The Listener

   a. Practice effects

The effects of practice on frequency discrimination by hearing-impaired listeners has apparently received little attention. However, the one study using hearing-impaired adults which was uncovered indicated that practice does reduce the median size of DLF and also the variability between subjects (Butler & Albrite, 1956). Unfortunately, the data obtained for each of five practice sessions was not given.

b. Individual differences

Individual differences between adults are large (Butler & Albrite, 1956; Hayes, 1951) but are not related to age (Hayes, 1951).

c. Children vs. Adults

Later comparisons will show large differences in performance between hearing-impaired adults and hearing-impaired children. This topic is given further consideration later.

2. The Stimulus

a. Effects of Frequency

In general DLF is relatively larger for the higher frequencies than for the lower frequencies when comparisons are made with normal listeners (McCandless, 1959), or between listeners with sensori-neural hearing disorders and conductive disorders (Butler & Albrite, 1956). In some types of hearing-disorder DLF may be larger than normal even at frequencies where sensitivity is normal (McCandless, 1959).

b. Effects of Intensity

The effect of intensity on size of DLF is different for hearing-impaired listeners than for normal listeners. Using test frequencies of 500, 1000 and 2000 Hz and Sensation Levels of 10, 25, and 40 dB Shutts (1950) found: (1) at 500 Hz the mean differences between the Sensation Levels were not significantly different from each other; and (2) at 1000 and

2000 Hz the differences were statistically significant between 25 and 40 dBSL but not between 10 and 25 dBSL. Comparison with a control group of normal listeners led him to conclude that DLF reaches its minimum value at least 15 dB nearer threshold for listeners with sensori-neural disorders than for listeners with normal hearing.

c. Interaction between Hearing Level and Size of DLF

The relation between Hearing Level and size of DLF is not well understood. When groups of listeners with relatively high Hearing Levels are compared with groups of listeners with relatively lower Hearing Levels, significant differences in size of DLF are found between groups, with the group having greater Hearing Levels showing significantly larger DLFs (McCandless, 1959; Houchins, 1962). However, high correlations between Hearing Level and size of DLF have not been found (McCandless, 1959; Houchins, 1962).

6. Frequency-Memory Studies with Children

Hudgins (1955) reported a preliminary survey of frequency discrimination performed on 16 profoundly deaf children. Details of the experiment were not given. The average DLF for the group was 12 percent and the range was 4 to 20 percent. Thus, for example, the average DLF for 1000 Hz was 120 Hz.

Strizver (1958) elaborated Hudgins work by testing 20 children with impaired hearing who were 14 to 17 years old. Seventeen of the children had average Hearing Levels greater than 80 dB (ASA) while the remaining three had average levels between 60 and 80 dB.

A modified method of constant stimuli was employed in which two tones having a particular Δf were alternately delivered until the listener reported the tones were either "same" or "different." A number of different Δfs were used which were delivered in random order.

Eight listeners were not tested at some frequencies because their Hearing Levels were very close to the reported threshold of discomfort. The average DLFs are given below along with the standard deviations and the range. The number of values on which the data are based is given in parentheses.

TABLE XII

DLFs FOR DEAF CHILDREN REPORTED BY STRIZVER

	500	1000	2000	Hz
$\bar{X}$	55 (20)	90 (19)	100 (12)	
SD	35	50	40	
Range	10-150	10-200	20-180	

Strizver concluded that while profoundly deaf children could discriminate differences in frequency; (1) the average size of DLF was much larger than in children with normal sensitivity, and (2) the variability between listeners was large.

Bradley (1959) was primarily interested in determining whether there was a relation between ability to discriminate differences in frequency and development of normal speech. He therefore tested three groups of children. The children in Group I had normal sensitivity and normal speech. The children in Group II had normal sensitivity and ". . . articulation defects severe enough to require speech therapy." The children in Group III had impaired hearing and impaired speech development. Each group was composed of 11 children between nine and fourteen years old.

A modified method of limits was used with a "same-different" response. The average DLFs are given below.

TABLE XIII

DLFs FOR THREE GROUPS OF CHILDREN REPORTED BY BRADLEY

Group		500	1000	2000	Hz
Group I	$\bar{X}$	6.8	7.4	8.8	
Group II	$\bar{X}$	13.4	22.0	41.0	
Group III	$\bar{X}$	68.4	94.3	194.0	

The null hypothesis that the scores of the three groups were the same was rejected. All groups at all frequencies were significantly different from each other. Bradley concluded that pitch discrimination was a contributing factor in the development of normal speech for hearing-impaired children and possibly also for children with normal sensitivity but defective articulation.

DiCarlo (1962) also tested three groups of children. He used a modified method of constant stimuli and required a "same" or "different" response. Group I consisted of 22 children with normal sensitivity and normal speech. Group II consisted of 20 children with normal hearing and defective speech. Group III consisted of 20 children with impaired hearing and defective speech. The age range within each group was 11 to 14 years.

The average values and standard deviations are given below.

TABLE XIV

DLFs FOR THREE GROUPS OF CHILDREN.
REPORTED BY DiCARLO

Group		500	1000	2000	Hz
I	$\bar{X}$	3.5	7.0	10.0	
II	$\bar{X}$	6.0	25.0	62.0	
III	$\bar{X}$	25.5	53.0	-	

(DLF was not reported for Group III for 2000 Hz because some children gave no response at 100 dB Hearing Level (ASA), the limit of the audiometer.)

Analysis of variance revealed no significant differences between the three groups for 500 Hz or between Groups I and II for 2000 Hz. The three groups did differ significantly at 1000 Hz.

Finally, Houchins (1962) was interested in determining whether there was a correlation between Hearing Level at a given frequency and the size of DLF at that frequency. He therefore tested three groups of children.

Group I consisted of 20 children between 11 and 12 years old who had normal sensitivity. Group II consisted of 20 children between 10 and 13 years old. These children were classified educationally as hard-of-hearing. Their average Hearing Levels (ISO) are given below.

250	500	1000	2000	4000	Hz
35	54	65	75	76	dB

Group III consisted of 18 children between 11 and 13 years old. These children were classified educationally as deaf. Their average Hearing Levels (ISO) are given below.

250	500	1000	2000	4000	Hz
55	74	90	95	101	dB

Houchins used a modified method of constant stimuli and actually tested his listeners on four separate occasions. However, during the first three test sessions he changed his values of Δf. The data he reported were from scores obtained during the last two test sessions. Houchins required his subjects to report the direction of frequency difference. The medians, means, and standard deviations for the three groups are given below.

TABLE XV

DLFs FOR THREE GROUPS OF CHILDREN.
REPORTED BY HOUCHINS

Group	Statistic	250	1000	2000	Hz
I	Mdn	4.5	8.0	13.5	
	$\overline{X}$	6.2	8.8	15.3	
	SD	5.3	4.9	9.4	
II	Mdn	11.0	37.5	73.0	
	$\overline{X}$	14.5	43.2	82.7	
	SD	8.5	32.0	50.0	
III	Mdn	29.0	74.0	-	
	$\overline{X}$	29.3	84.1	-	
	SD	17.2	43.1	-	

The data were not normally distributed and therefore a Kruskall-Wallis one-way Analysis of Variance was used to show that there were significant differences between groups in size of DLF.

Coefficients of correlation between Hearing Level at the test frequencies and size of DLF were also computed and the values which were obtained are given below.

TABLE XVI

CORRELATION BETWEEN HEARING LEVEL AND DLF.
REPORTED BY HOUCHINS

Frequency	Group II	Group III
250	.13	.17
1000	.12	-.07
2000	.16	-

These correlations were not significant.

In an effort to expand the range of Hearing Levels and DLFs used in calculating the correlation coefficient the two groups of hearing-impaired children were combined. The correlation between Hearing Level and size of DLF at 250 and 1000 Hz was .36 and .24 respectively. These correlations were also not significant.

Houchins concluded that altogether Group II had both an average Hearing Level and an average DLF that was lower than that of Group III, the two variables were not necessarily related to each other in a systematic way for the children within each group or for the two groups combined.

7. Conclusion

The data from hearing-impaired listeners are summarized below.

TABLE XVII

SUMMARY TABLE OF DLFs OBTAINED FROM HEARING-IMPAIRED CHILDREN AND ADULTS

Children					
Author	250	500	1000	2000	Hz
Strizver		55	90	100	
Bradley		68	94	194	
DiCarlo		26	53		
Houchins (H-H)	14		43	83	
(Deaf)	29		84		
Adults					
Author	250	500	1000	2000	Hz
Butler & Albrite		2.6	4.5	7.6	
Shutts		7.0	10.2	14.5	
Hayes		15.5	18.7	31.5	
McCandless		5.6	23.0		

The differences between the child and adult groups are striking. It is plausible to assume that since the adults had normal hearing as children, they had learned to make relatively fine discriminations as children naturally do. In contrast, the children tested in the experiments which were described had never had normal hearing and had never learned to make fine discriminations of frequency. However, they might learn to do so with practice. An attempt to demonstrate this thesis was the major purpose of this dissertation.

CHAPTER IV

PILOT STUDY OF FREQUENCY DISCRIMINATION

A. Introduction

The review of the literature showed that on the average: (1) listeners with impaired hearing show larger DLFs than listeners with normal hearing; (2) while even children with normal hearing show larger DLFs than normal adults the differences between hearing impaired children and impaired adults is relatively much larger; and (3) DLF depends on many factors of stimulus and procedure. It was suggested at the end of the review that the relatively large DLFs found in hearing-impaired children when compared with hearing-impaired adults was due to a lack of practice. The adults had had informal practice in learning to discriminate environmental sounds, including speech, during their childhoods when their hearing was normal.

An alternative explanation is that the differences are due to experimental error. However, the specific sources of possible error were considered to be too difficult to recognize and evaluate without first-hand experience in actually measuring the DLF of a number of hearing-impaired children.

One purpose of the present experiment was to see if the results of previous experiments would be replicated with a new sample of hearing-impaired children. A second related purpose was to gain knowledge about how best to conduct experiments designed to measure ability to discriminate differences in frequency.

The following general considerations guided the design of the present experiment:

1. Comparison with previous data
   a. In order to compare the results of the proposed experiment with previous results a frequency-memory experiment was necessary.
   b. The response required from the child should also be the same that was used in previous experiments. Strizver (1958), Bradley (1959), and DiCarlo (1962) had all required a "same" or "different" response.
   c. The method of stimulus delivery should be similar to that used in previous experiments. The majority of authors delivered alternating stimuli until the listener made a response.
2. The test should be rapid to administer. The method of limits was therefore chosen.

B. <u>Procedure Used in the Pilot-Study of Frequency Discrimination</u>

<u>Subjects</u>: The same subjects tested in the experiments described in Part I were used. However, responses from only

54 subjects were scored. The reasons why the remaining 18 subjects did not complete this test will be given in the Results section.

Apparatus: A block diagram of the stimulus generator is shown in Figure 4. Notice that two independent electronic switches were used to deliver alternately the standard and comparison tones. A single two-channel switch had been used initially in order to replicate the apparatus of Strizver (1958) and of DiCarlo (1962). However, a very detectable and distracting transient was present while one tone was decaying and the second tone was building up. To eliminate the transient, two independent channels were used to control rise and decay time, duration of signal, and duration of silent interval between tones.

Stimuli and Psychophysical Procedure: Estimates of DLF were obtained by the method of limits. Tests were made around standard frequencies of 500 and 1000 Hz. The standard and test signals alternated continuously. Each signal was 400 msec long. A 100-msec silent interval separated one signal from the next. The rise and decay time of the signals was 10 msec. Signals were delivered 20 dB above the listener's threshold. Some Ss were tested with the 500-Hz tone first; others were tested with the 1000-Hz tone first.

Procedure: Prior to the test the subject was given a 2" by 3" card on which was printed the following. "Today you will listen to some sounds. Sometimes you will hear

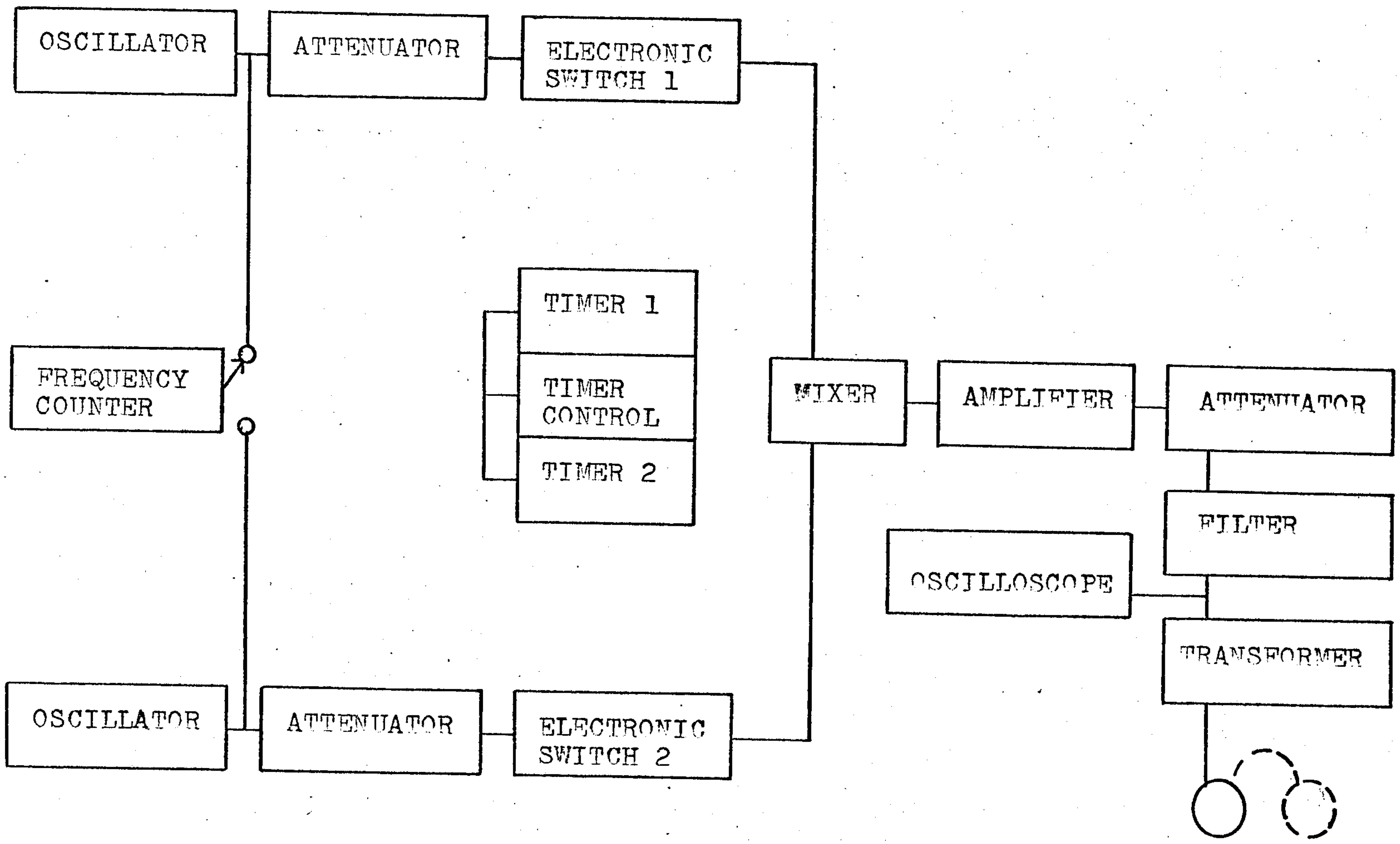


FIGURE 4. BLOCK DIAGRAM OF APPARATUS USED IN PILOT STUDY OF DIFFERENCE LIMEN FOR FREQUENCY.

this: _ ‾ _ ‾ . Sometimes you will hear this: _ _ _ _ . Show me which sounds you hear."

On the desk, behind which the subject sat, were two 6" by 6" cards displaying the 2 line configurations.

The subject was encouraged to read the instructions aloud. When he came to the vertically displaced lines, he was given a sample of signals approximately 1/3 octave apart and encouraged to point to the response card with the vertically displaced lines. He then proceeded to continue reading until he came to the row of broken lines. Here the subject was given a sample of signals that were the same in frequency. If S did not spontaneously point to the appropriate card, he was encouraged to do so.

As a check to be sure the subject understood the task the signals were again set 1/3 octave apart and delivered to S. If he gave the correct response the signals were removed, set to equal frequencies, and redelivered. If S again responded correctly the test was begun.

The test started at the approximate 1/3 octave difference used for the demonstration. For some Ss this initial test tone was higher (for example, 650 Hz) than the standard tone (500 Hz). For others it was lower (300 Hz).

The experimenter slowly turned the frequency control of the oscillator until S shifted his response from the vertically displaced lines to the row of lines. This frequency was read from the frequency counter and recorded. The experimenter then continued turning the dial in the same direction until S again switched his response. This frequency was also recorded. If this first run began above the standard frequency, the next run began below it.

A total of five such runs were made during which ten responses were made: five judgments of "just same" and five judgments of "just different." The first of each of these judgments was considered practice and was not included in estimating DLF.

C. <u>Results and Discussion of Pilot Study of Frequency Discrimination</u>

It was previously mentioned that only 54 of the 72 subjects tested gave scorable data. Seven children failed to understand instructions. Their responses were so erratic from trial to trial that there appeared to be no specific criterion for response. Three listeners reported that the stimuli were always different even when they were at the same frequency and amplitude. One listener reported that the signals were always the same even for Δfs of over 200 Hz. One subject reported that she heard nothing even at the maximum output permitted by the apparatus (132 dB SPL). Finally, four children gave scorable results at 500 Hz but reported hearing nothing at 1000 Hz.

The initial step in data analysis was to compute the average DLF above and below the standard frequencies and the dispersion around these means. These data are given below.

	500_B	500_A	1000_B	1000_A	
$\overline{X}$	37.2	33.7	57.5	68.1	Hz
SD	19.8	18.5	36.1	38.7	

Inspection of the table shows different average values above and below each standard frequency. These differences were tested for statistical significance by using *t* tests adjusted for matched samples (Underwood, *et al.*). The average differences for variable frequency above and below each standard frequency were not statistically different and therefore were combined. This finding agrees with results obtained in several other studies (Shutts, 1950; Hayes, 1951; Bradley, 1959).

Inspection of the standard deviations of DLFs above and below the 500 Hz standard frequency suggests that the distribution of scores is also independent of the direction of frequency difference. The same conclusion is made about the distribution above and below the 1000 Hz standard. Therefore the two standard deviations at each frequency were averaged.

The median, mean and standard deviation of the pooled data for each frequency are given below.

Comparison of the mean values obtained in this study with the data reported by other investigators indicates that the closest arrangement is with the data of DiCarlo (1962).

TABLE XVIII

SUMMARY OF DLF-DATA FROM PILOT STUDY

	500	1000	Hz
Mdn	36.0	55.5	
$\bar{X}$	35.5	62.8	
SD	19.2	37.5	

At 500 Hz the median and mean values obtained in this study are approximately 10 Hz larger than DiCarlo's mean DLF, and at 1000 Hz the mean value here is approximately 13 Hz larger than his .

As was true of the other studies in which children with impaired hearing were tested, the average DLFs obtained in this study are much larger than average DLFs obtained from either children with normal sensitivity or from adults with impaired hearing. Confirmation of the previous findings supports the notion that the differences in initial performance between hearing-impaired children and adults is real and that the underlying sources of these differences should be investigated.

Some ideas about the subjects' performance can be obtained by further study of the present data. For example, the table given above showed that the median and mean values obtained at 500 Hz were approximately equal. In contrast, at 1000 Hz, the median was approximately 12 Hz smaller than the mean. This suggests that the distribution of DLF_{500} is different from the distribution of DLF_{1000}. That this is actually the case is seen in the following histogram.

The distribution of DLF_{500} is positively skewed. This agrees with the data reported by Houchins (1962) for both hard-of-hearing and deaf children. The distribution of DLF_{1000} is difficult to characterize. However, the two distributions do not look the same.

The dissimilarity of the two distributions suggests that there might be little relation between a subject's performance under one stimulus condition when compared with performance under the second condition. A quantitative description of the degree of linear relationship between individual DLFs at 500 and 1000 Hz is given by the coefficient of correlation. The correlation between DLF_{500} and DLF_{1000} was found to be 0.27, thus indicating little relation between the two scores.

Houchins (1962) also reported the correlation between DLFs obtained at different test frequencies. For the group labeled Deaf he found a correlation of 0.13 between DLF_{250} and DLF_{1000}. This agrees with the results of the present study. In contrast, for the group labeled Hard-of-Hearing he found the following correlations.

DLF_{250}-DLF_{1000}	DLF_{250}-DLF_{2000}	DLF_{1000}-DLF_{2000}
0.52	0.46	0.56

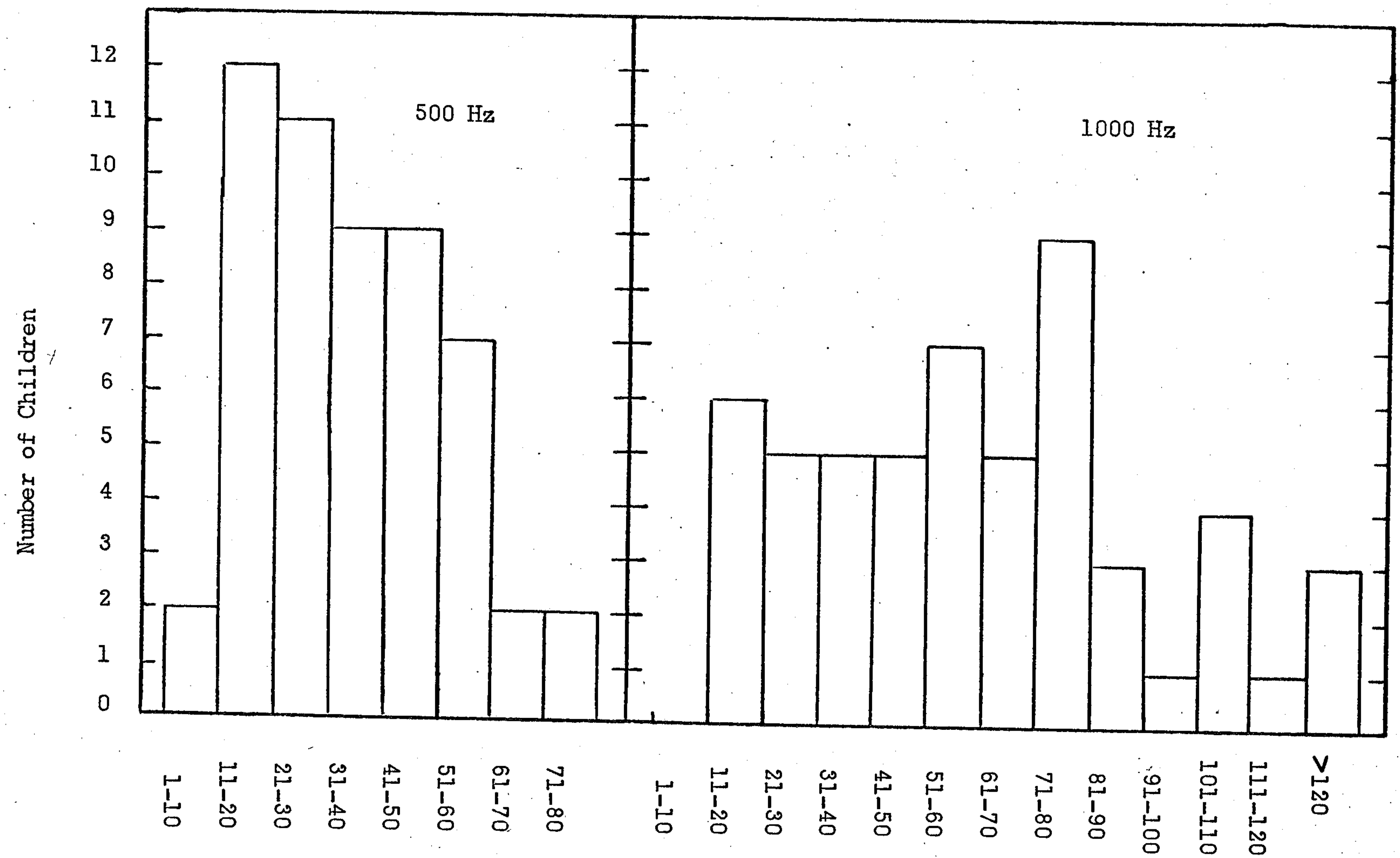


FIGURE 5. DISTRIBUTION OF DIFFERENCE LIMEN FOR FREQUENCY FROM THE PILOT STUDY.

This suggests a moderate degree of relation between DLF at one frequency and another.

Why the degree of relationship between size of DLF should differ for the two groups is unknown. Obviously Houchin's two groups differed in average sensitivity to sound. However, recall that he found no correlation between Hearing Level and size of DLF.

The results of the present study, which confirm Houchin's data, lead to the following conclusion. For a group of children with severely impaired hearing, the average size of DLF increases with the increase in frequency. However, for an individual child, the amount of increase is not predictable; that is, there is no linear relation between size of DLF at one frequency and another. It is premature to discuss the implications, both theoretical and practical, of this conclusion since data are not yet available from a group of hearing-impaired listeners who are performing at the physiological and perceptual limits of their ability and who might thereby show less variability between stimulus conditions. Nevertheless, this topic would appear to be an important one deserving further investigation.

It was mentioned above that Houchins found a low correlation between Hearing Level and Size of DLF. Correlations were also computed from the data obtained in this study. The correlation between Hearing Level at 500 Hz and DLF_{500} was 0.23. The correlation between Hearing Level at 1000 Hz and DLF_{1000} was 0.30. These results agree with Houchin's findings.

One hypothesis generated by these results is that a given hearing disorder can reflect itself differently in Hearing Level and DLF scores and that the two scores need not be related. Support for such an hypothesis is McCandless' (1959) finding that a group of subjects who had normal thresholds at 2000 Hz but not at 4000 Hz showed significantly larger DLFs at 2000 Hz than did a group of subjects who had normal thresholds at both 2000 and 4000 Hz. However, it remains to be seen if this hypothesis will be supported by data from highly trained listeners with impairments similar to those tested by McCandless.

Is there any evidence that the children tested in this study were not performing at the limits of their ability? One index of performance is the reliability of scores under similar test conditions. Recall that the first data of Table XVIII showed an average DLF and a standard deviation for scores ~~above and below each standard deviation for scores~~ above and below each standard frequency. For a particular frequency there was no significant difference between mean value above and below the standard and the standard deviations were similar. This might suggest that individual subjects also showed approximately the same size DLF above and below the standard. If this were true, the correlation between DLF_A and DLF_B would be near 1.0. The actual correlations are given below.

	500	1000	Hz
r =	0.55	0.83	

The correlation coefficient of 0.55 at 500 Hz indicates that, at least for some subjects, there was considerable variability between DLF above and below the standard. For example, one subject gave a DLF of 82 Hz above the standard and a DLF of 29 Hz below the standard. A second subject gave a DLF of 38 Hz above the standard and 90 Hz below. At the other extreme, one subject gave a DLF of 16 Hz above the standard and a DLF of 15 Hz below. Another subject gave identical DLFs of 49 Hz above and below the standard.

The fact that some subjects showed relatively large differences in size of DLF above and below the standard suggests two different hypotheses. One is that the data are valid and that, in fact, small directional shifts in the comparison frequency can be associated with large shifts in size of DLF. The second hypothesis is that some listeners had so little experience in the listening task that they were unable to establish a single and stable criterion for what constituted a "same" stimulus as opposed to a "different" stimulus. The data obtained in this experiment cannot be used to accept or reject either hypothesis. However, some comments are offered in retrospect concerning the second hypothesis.

The choice of the "same-different" response turned out to be a poor one. The subjects under test were known to have had only limited experiences in discriminating between sounds. Nevertheless, a response was chosen which assumed that all the listeners were familiar with the concept of pitch differences. The establishment of a criterion of what constituted a pitch difference was left completely to the subjects and there was no way the experimenter could check the validity of the criterion. The experimenter could only assume that qualitative differences other than pitch would never occur. However, when a listener required a frequency difference of 50 or more cycles before he would say different such an assumption is questionable. It is possible that the response criterion was a difference in loudness rather than pitch, or perhaps, depending on the stimulus condition, sometimes the criterion was "pitch difference," sometimes "loudness difference."

The choice of the method of limits was a poor one. Recall that Boring (1940) suggested that by this method, the spread of the "equal" category was measured. In the method of limits, the subjective certainty of what constitutes a "same" or "different" stimulus is left to the subject and cannot be measured by the experimenter. Thus one subject might require 100 percent confidence before giving a particular response while another subject might require only 60 percent confidence. In the case of untrained listeners the confidence criterion could be expected to be unstable. This would be reflected by as large shifts in size of DLF under similar stimulus conditions. The method of constant stimuli would have been a more suitable method for measuring DLF.

In conclusion, it is suggested that this experiment has confirmed the finding that, on the average the initial size of DLF of hearing-impaired children is larger than the DLF of hearing-impaired adults. Two other findings were also confirmed. One is the low correlation between the size of DLF for different frequencies. The second is a low correlation between Hearing Level and size of DLF. Repeated measurements from the same subjects are required to check the reliability of these findings.

It is further suggested that some of the variability of subject's responses was due to employment of methods which left both the definition of response criterion and the definition of confidence criterion to the subject but gave the experimenter no way of measuring either.

Finally, repeated measurements with more adequate methods are needed in order to better understand the ability of hearing-impaired children to discriminate small differences in frequency. Therefore, the experiment reported in the next section was designed and performed.

CHAPTER V

MAIN STUDY OF FREQUENCY DISCRIMINATION

A. Introduction

As mentioned in the initial introduction, there were several purposes for further experiments dealing with frequency discrimination. These are reviewed here.

The most important purpose was to determine whether practice influenced the size of the DLF of hearing-impaired children. To investigate this problem three groups of children were tested.

One group had normal hearing. This group was included to obtain an estimate of optimum performance with the actual tests used. The normal children were tested only once, or in a few instances, twice. The other two groups of children had impaired hearing. These children were tested three times, and in addition some of these children were tested seven additional times.

The second purpose of this experiment was to check the validity of measurement of DLF. In the preceding experiment it was suggested that subjects who showed large DLFs might actually have responded to differences in loudness rather than differences in pitch. To further investigate this notion a condition was included in which it was expected that the children would hear differences in loudness as well as pitch. However, the condition was so controlled that in order to identify the direction of frequency change correctly, intensity differences would have to be ignored.

The third purpose was to determine whether children who showed relatively large DLFs during three test sessions could show reduction in the size of DLF with further practice. Said another way, this portion of the experiment investigated whether the variability between subjects which was observed in the previous experiment was due to fixed differences in ability or to differences which could be reduced by further practice. Six children who showed large DLFs during the first three test sessions were tested seven more times in order to answer this problem.

The fourth purpose was to examine again the relation between Hearing Level and size of DLF. Therefore a group of children with relatively smaller Hearing Levels was tested as well as a group with relatively greater Hearing Levels.

B. Procedure

Subjects: The seven children in Group I consisted of four boys and three girls who had normal hearing. They were children of friends and relatives of the experimenter and were all highly motivated to do well in the experiment. Their average age was 11 years, 1 month. The range was 9 years, 8 months to 12 years, 4 months.

The 21 children in Group II consisted of 12 boys and 9 girls who were classified for educational purposes as hard-of-hearing. They were enrolled in special classes in regular public schools situated in the western suburbs of Chicago, Illinois. The average age of these children when tested was 12 years, 3 months. The range was from 9 years, 7 months to 15 years, 1 month.

No restriction was placed on selection for inclusion into this group except for the following one. By arbitrary decision, Hearing Level in the test each could be no greater than 70 dB (ISO) at 250 Hz and 80 dB at 500 Hz. The Average Hearing Levels and sound pressure level re .0002 dynes/cm^2 (SPL) equivalent for octave intervals between 250 and 2000 Hz are given below.

TABLE XIX

MEAN THRESHOLDS OF THE HARD-OF-HEARING GROUP

250	500	1000	2000	Hz
40.5	50.2	63.6	73.3	Hearing Level
65.0	61.2	70.1	81.8	SPL

The 23 children in Group III consisted of 15 boys and 8 girls, enrolled at Central Institute for the Deaf, and classified for educational purposes as deaf. The average

age of this group was 13 years, 10 months. The range was 10 years, 4 months to 16 years, 8 months.

No restriction was placed on selection for inclusion into this group except that Hearing Level could not be greater than 85 dB at 250 Hz and no greater than 100 dB at 500 Hz. (One exception was made for one boy who had a 90 dB Hearing Level at 250 Hz.)

The average Hearing Levels and thresholds in SPL are given below.

TABLE XX

MEAN THRESHOLDS OF THE DEAF GROUP

250	500	1000	2000	Hz
68.5	81.1	90.0	101.7	Hearing Level
93.0	92.1	96.5	109.2	SPL

Apparatus: Since it was necessary to test the children in Group I in their homes and the children in Group II in the schools that they attended, a high quality portable tape recorder (Ampex 602) was used to record and reproduce the test stimuli. For the actual delivery of stimuli the apparatus diagrammed in Figure 6 was used. With this arrangement, the level of the third harmonic, which is especially prominent with recorded pure tones, was more than 50 dB below the level of the fundamental.

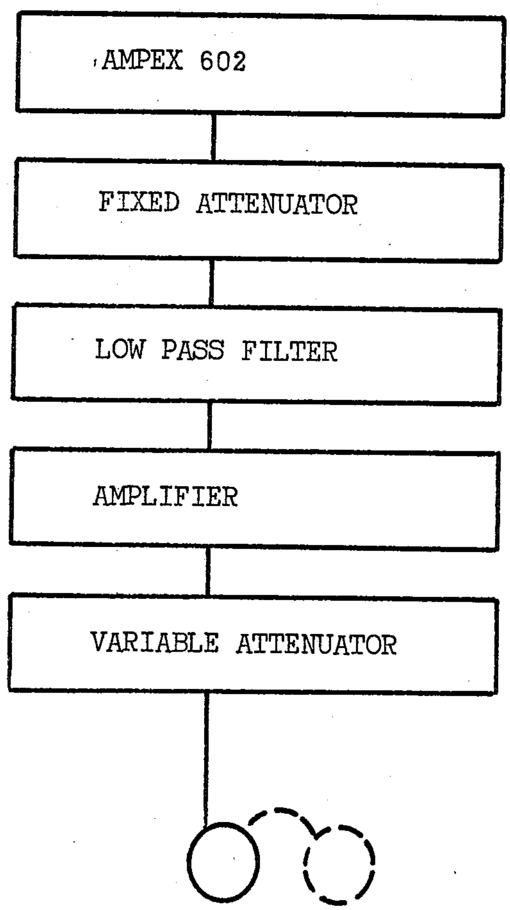


FIGURE 6. BLOCK DIAGRAM OF APPARATUS USED IN MAIN DIFFERENCE LIMEN FOR FREQUENCY EXPERIMENT.

Prior to the first test, audiograms were obtained from the children in Groups I and II with a Zenith audiometer, Model ZA 110 TW. Recent audiograms were available for Group III.

Method: The method of constant stimuli and a roving standard was used. This means, for example, when the standard frequency was 500 Hz, that it might be either the first or second of a pair of stimuli. The comparison tone was always higher in frequency than the standard. This method was used in order to keep the test as short as possible and was considered permissible because, on the average, DLFs obtained above and below the standard were not significantly different in the pilot study.

Stimuli: Tones with rise and decay times of 10 msec were delivered in pairs, each tone being one second long. The interstimulus interval was 0.5 sec. A response interval of 3.5 sec. separated pairs of tones.

Standard tones of 250 and 500 Hz were used. The choice of the comparison frequencies was based on inspection of DLFs which previous authors had reported. Since it was evident that variability between subjects was great, a geometric progression of Δfs was used rather than a linear one.

The 250 Hz standard was paired with the following frequencies: 298, 274, 262, 256, and 253 Hz. These frequencies were delivered to Groups I and II. Group III also received 346 Hz. The 500 Hz standard was paired with 564, 532, 516, 508 and 504 Hz. Group III also received 628 Hz.

The standard frequency was paired with each comparison frequency 10 times and appeared first on five trials. Pairs of stimuli were delivered in blocks of 10. The first block contained the largest differences in frequency. Successive blocks contained successively smaller increments of Δf. Within a block the order of paired frequencies was random. The time required to deliver the 50 pairs of stimuli to Groups I and II was 250 sec. The time required to deliver the 60 pairs of stimuli to Group III was 300 sec.

It will be recalled that in a second test condition there was a difference in amplitude between the first and second stimulus of a pair. In this condition, hereafter called the variable-amplitude condition as opposed to the fixed-amplitude condition described above, the amplitude of the second stimulus was fixed. The amplitude of the first stimulus was either 2, 4, 6, 8, or 10 dB less intense.

Amplitude differences of 2 to 10 dB were considered to be sufficient to neutralize the effects of possible fixed differences in the loudness of suprathreshold tones, because previous data gathered at Central Institute for the Deaf (CID) indicated that average thresholds for 250, 500 and 1000 Hz when expressed in SPL were approximately equal (Elliott). This finding was also true for the sample of CID children used in this study. It is also true at 250 and 500 Hz for Group II. Although for Group II, the average difference in threshold at 500 and 1000 was 9 dB, there is no reason to assume that the difference in threshold sensitivity at 500 and 564 Hz would be more than 10 dB.

Each difference in amplitude was used twice with each Δf and the order in which the amplitude differences were delivered was random. In all other respects the fixed amplitude and variable amplitude tests were identical. Since there were two standard frequencies each listener received four tests during a session. A test session typically required 20 to 30 minutes to complete.

Each test was preceded by two samples of the largest Δf. In the variable amplitude condition, a ΔI of 10 dB was used. Two scrambles of each test were made. Therefore, for the initial set of three tests, a listener never heard a particular order of stimuli more than twice.

The level at which stimuli were delivered varied somewhat between listeners. The subjects with normal sensitivity were tested at 30 dB SL. Listeners with impaired hearing were tested at comfortable Sensation Levels or, where necessary, at the maximum output of the audiometer which was 130 dB SPL. For most listeners, signals were 20 dB or more above threshold.

Recall that six children were tested seven additional times. For these tests two new scrambles of the 500 Hz fixed amplitude test were made. In this test, each block of Δf contained 20 pairs of stimuli. The Δf of 4 Hz was deleted from this test. The variable-amplitude tests remained the same. These children were tested at 500 Hz only.

Procedure: The children with normal sensitivity were tested first. The test ear was chosen in random fashion and an audiogram was taken. Each child was tested individually. Prior to the first test, the child was told that he was to listen to a number of pairs of sounds. Sometimes the sounds would go High-Low; sometimes they would go Low-High. The child was instructed to tell the experimenter which way each pair of sounds went.

Next the child was given the samples. He was told the first pair would go Low-High (or High-Low) and then allowed to listen to the stimuli. He was then given the order of the second set and the sample.

The samples were then given again without labeling the direction of frequency change. If the child gave the correct responses the test was begun. If he did not, the labels and samples were repeated until correct responses were given.

Responses were recorded by hand by the experimenter. After each correct response the experimenter gave positive reinforcement by saying "good" or nodding his head. After an incorrect response he did nothing except record the response.

Similar instructions were given before the variable-amplitude test. The subject was told that the second sound would always be louder but that he was to ignore the difference in loudness.

Since the normal children were usually tested at their homes, most of the children were tested only once or twice. As will be seen, this was usually all the practice necessary to correctly identify even the smallest Δf with better than 75 percent accuracy. For the normal children, order of test presentation was random.

The hard-of-hearing children (Group II) were tested second. Essentially the same procedure was used. However, some modifications were made. After just a few of the children had been tested for the first time it became evident that fewer errors were made on the 250 Hz tests than on the 500 Hz tests. Thereafter, the 250 Hz tests were always given first during the first session. It was also evident that more errors were made on the variable amplitude conditions than on the fixed amplitude conditions. An initial plan to randomize order of presentation during the second and third test sessions was therefore abandoned. Thus, for the first test session the order of test presentation was 250 Hz fixed amplitude, 250 Hz variable amplitude, 500 Hz fixed amplitude, and 500 Hz variable amplitude. On subsequent days the order of frequencies was randomized but not the order of amplitude.

One other procedural modification was made. Recall that the children with normal sensitivity were given trial by trial feedback; a nod or "good" when correct, no response when incorrect. The data, to be given later, will show that these children made few errors. In contrast, some of the hard-of-hearing and deaf children initially made numerous incorrect responses even for the larger Δfs. Rather than give a child too many negative reinforcements and risk having the test become too threatening or frustrating, the experimenter terminated the test after two successive blocks of Δf were identified with less than 75 percent accuracy. This means, for example, that a child who was having difficulty in discriminating frequency differences at 500 Hz might receive only Δfs of 64, 32, and 16 Hz during the first session; Δfs of 64, 32, 16, and 8 Hz during the second session; and all Δ fs during the third.

The deaf group was tested third. The procedures used with this group were identical to those described above. However, as noted earlier, the Δf of 96 Hz was added to the 250 Hz test and the Δf of 128 Hz was added to the 500 Hz test. This change was considered necessary because in some of the test conditions some of the hard-of-hearing children experienced such difficulty that they were not able to correctly identify even the largest Δfs. Since it was assumed the deaf children, as a group, would have greater difficulty discriminating differences in frequency the larger Δ fs were added.

C. Results

The data were analyzed in the following way. For each subject the percent of correct responses obtained for each Δf was recorded. These data were plotted on a graph which had percent correct as the ordinates and Δf as the abscissas. The points were connected by straight lines. The frequency difference corresponding to 75 percent-correct was taken as the estimate of DLF.

For 6 percent of the responses obtained from the hard-of-hearing and deaf children, scores dropped below 75 percent accuracy. In these cases, two estimates of DLF were averaged to give the final value. The individual data of all the subjects tested in this experiment are given in Appendix I.

Inspection of the data indicated that, in accord with Houchins (1962) findings, the distributions of DLFs were not normal. Therefore the median was chosen as the measure of central tendency and non-parametric statistics were used to test for differences between various conditions. The principle results are given below.

The data from Group I show that even without practice, more than half of the children with normal sensitivity were able to discriminate correctly the smallest frequency differences with better than 75 percent accuracy under both amplitude conditions. However, they reported that the variable amplitude test seemed harder; that is, they were less confident about the correctness of their judgments. Median values were similar to results previously reported; that is, 4.5 Hz at 250 Hz (Houchins, 1962), and 3.7 Hz at 500 Hz (DiCarlo, 1962). Therefore, it was concluded that

TABLE XXI

MEDIAN DLFs OF THE THREE GROUPS OF CHILDREN

		Frequency					
		250			500		
Group	Amplitude	1	2	3	1	2	3
I	Fixed	3			4		
II		17.5	11	10.5	31.5	25.5	15.8
III		18	14	9 +	48	28.5	24 +
I	Variable	3			4		
II		36	33	18	64	56	36 +
III		42	38	22 +	104	54	48 +

I = Normal sensitivity
II = Hard-of-hearing
III = Deaf

\+ Indicates statistically significant shift in DLF over the three sessions.

Confidence Level = 5 percent or less.

the tests were valid and could be used to measure DLF with hearing-impaired children.

Effects of Practice

Inspection of the median scores obtained by the two hearing-impaired groups shows a progressive decrease in the size of DLF for all stimulus conditions. Furthermore, as can be seen from Figures 7 and 8, there is a progressive shift in the distributions of DLF toward progressively smaller DLFs. For all conditions there is either a progressive increase in degree of skew to the right or a progressive

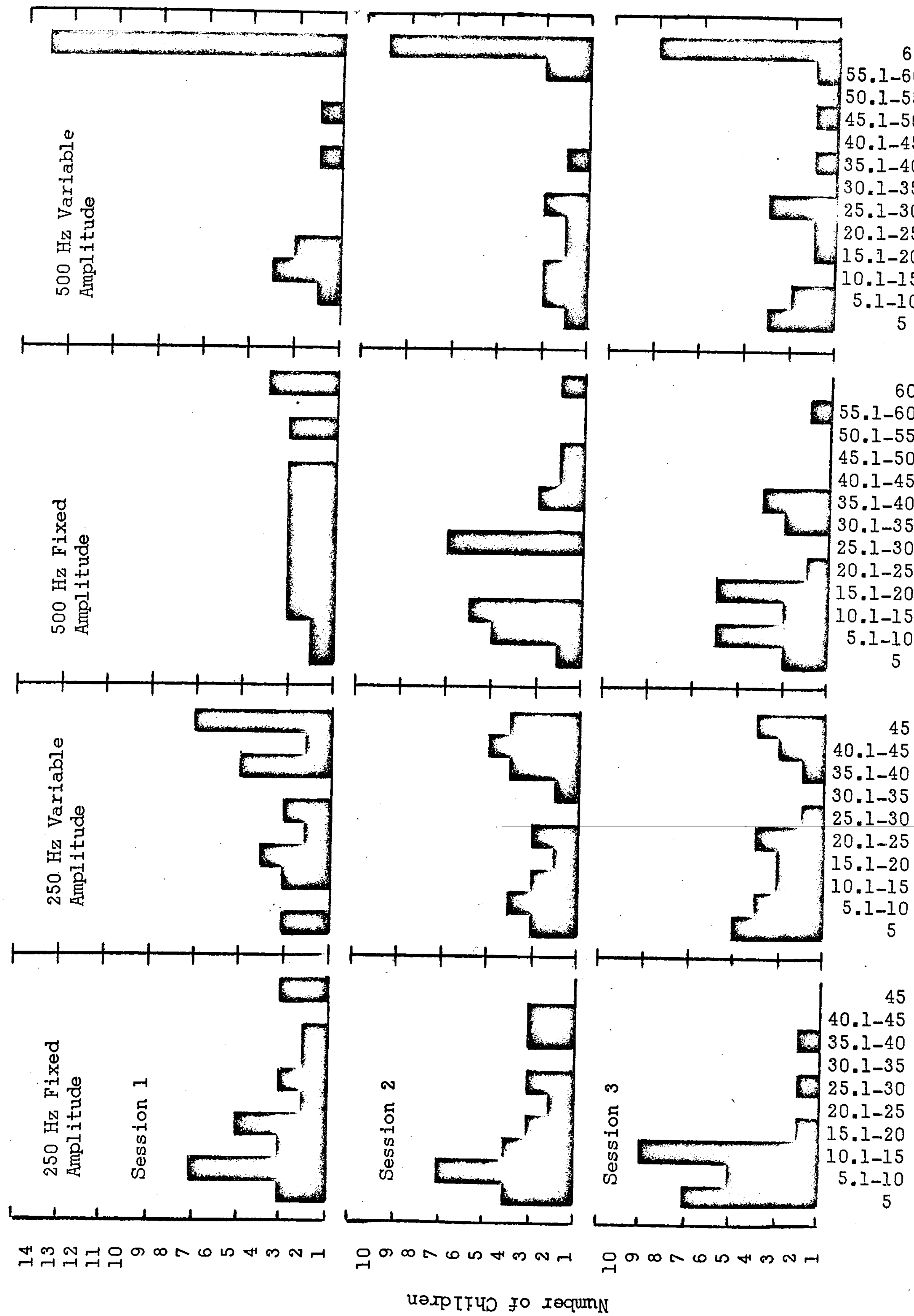


Figure 7. Distribution of DLFs for Hard-of-Hearing Children.

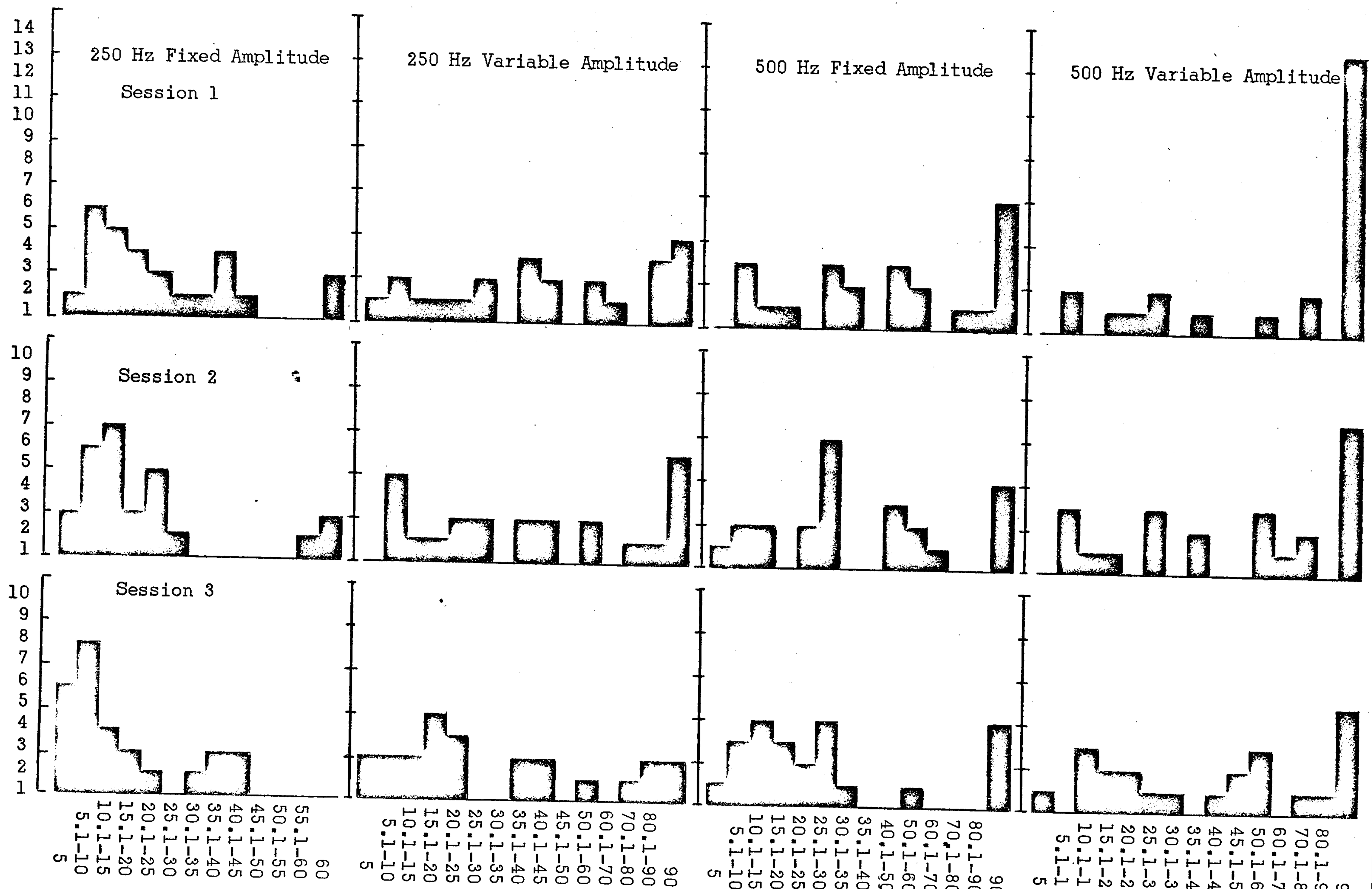


Figure 8. Distribution of DLFs for Deaf Children.

movement of the distribution from skew to the left toward skew to the right. Both findings support the conclusion that practice reduces the size of DLF of hearing-impaired children.

The statistical significance of the practice effect was assessed by a series of Friedman Two-Way Analyses of Variance by Ranks (Siegel, 1956). These analyses indicated that for the deaf group, significant decreases in the size of DLF occurred over the three test sessions for all stimulus conditions. For the hard-of-hearing group, only the 500 Hz variable-amplitude condition shows a statistically significant decrease in size of DLF. Inspection of the individual data suggested two reasons why statistical significance was not reached under the other conditions. One, some children who initially scored well below the median, gave DLFs on Session Three which were one or two Hz larger than on Session One. These children were probably near their maximum performance on the initial test and therefore subsequent scores reflect fluctuations around asymptotic performance. Second, some children who initially showed DLFs above the mean showed highly variable performance over the three test sessions. These children probably either did not understand the task well or were poorly motivated for reasons unknown to the experimenter.

Analyses which are described later indicated there were no statistically significant differences between the

DLFs of the hearing-impaired children in the two groups and therefore the data could be pooled. Results of Friedman Two-Way Analyses of Variance for this larger group indicated highly significant decreases in size of DLF over the three test sessions for all stimulus conditions. It is therefore concluded that even a small amount of practice can serve to reduce significantly the median DLF of hearing-impaired children.

It should be recalled that to examine further the effects of practice on size of DLF six children who initially showed large DLFs were given additional practice sessions with the 500 Hz standard. The data obtained from these children are given in Table XXII.

Inspection of the individual data indicates that initially there was considerable variability between subjects but that the scores subsequently became more homogeneous. Furthermore, although there are day-to-day fluctuations in the size of the individual DLFs over the 10 sessions, the DLFs do become smaller with extended practice.

For the fixed-amplitude condition there is a rapid initial decline in the median DLF over the first two sessions. Then for the next six sessions the median shows a relatively fixed value. This is followed by a further reduction in the mediam value which is stable for the last two sessions. Similar changes in the median value of DLF are evident for

TABLE XXII

INDIVIDUAL SCORES AND MEDIAN DLFs OBTAINED FROM EXTENDED MEASUREMENTS WITH SIX DEAF CHILDREN

	Sessions									
Fixed-Amplitude										
Subject	1	2	3	4	5	6	7	8	9	10
1	59	49.5	27.5	17	45	15	24	24	15	14.5
2	48	56.5	20	29.5	30	37.5	26	25	13.5	13
3	128	104	27	29	12	15	12	24	13.5	11
4	96	30	30	16	19	14	12.5	20	8	12
5	118	48	96	46	46	28	64	29.5	13	16
6	56	48	15.5	16	22.5	16	16	22.5	19	13.5
Median	77.5	48.8	27.2	23	26.2	15	20	24	13.5	13.2
Variable-Amplitude										
Subject	1	2	3	4	5	6	7	8	9	10
1	40	80	48	23.5	14.5	14.5	27	12	29.5	24
2	128	128	59	59	59	24	24	15	14.5	28
3	128	59	34	48	59.5	48	26	52	24	20
4	128	128	120	128	40	48	22.5	14.5	7.5	12
5	128	54	24	40	40	40	48	44	56	24
6	118	29.5	44	14.5	26	20	16.5	29.5	19	13.5
Median	128	69.5	41	44	40	32	25	22.2	21.5	22

the variable-amplitude condition. There is an initial decline in size of DLF over the first two sessions which is followed by three sessions showing relatively fixed values. On the sixth session the median DLF shows a further transition to the again relatively fixed values seen during the last four sessions.

In order to show the effects of practice on performance with some of the day to day variability smoothed out the median values were averaged over blocks of two sessions. The resultant learning curves are shown in Figure 9.

The fixed-amplitude learning curve makes very evident the plateau which extends over the three middle blocks of the experiment. Thereafter the DLF drops to approximately half the value obtained in the second block. Note that this final median DLF of 13.3 Hz is well below the group median for deaf children on the third session of the previous experiment. Furthermore, all 12 individual DLFs obtained during this last block are below the group median; thereby further showing the consistency of the practice effect.

The learning curve for the variable-amplitude condition tends to obscure the initial plateau over Sessions 3 to 5 because of the rapid descent between the fifth and seventh sessions. Nevertheless, the curve does show a progressive decrease in size of DLF as a function of amount of practice. As for the fixed-amplitude condition, the median for the fifth block is approximately half the median for the second block and is less than half the group-median reported for deaf children in the previous experiment.

The data from these children further emphasize the effects of practice on size of DLF. Furthermore, they suggest that at least some of the variability seen initially between subjects can be reduced by giving systematic practice in making frequency discriminations.

These findings, in conjunction with those of the previous

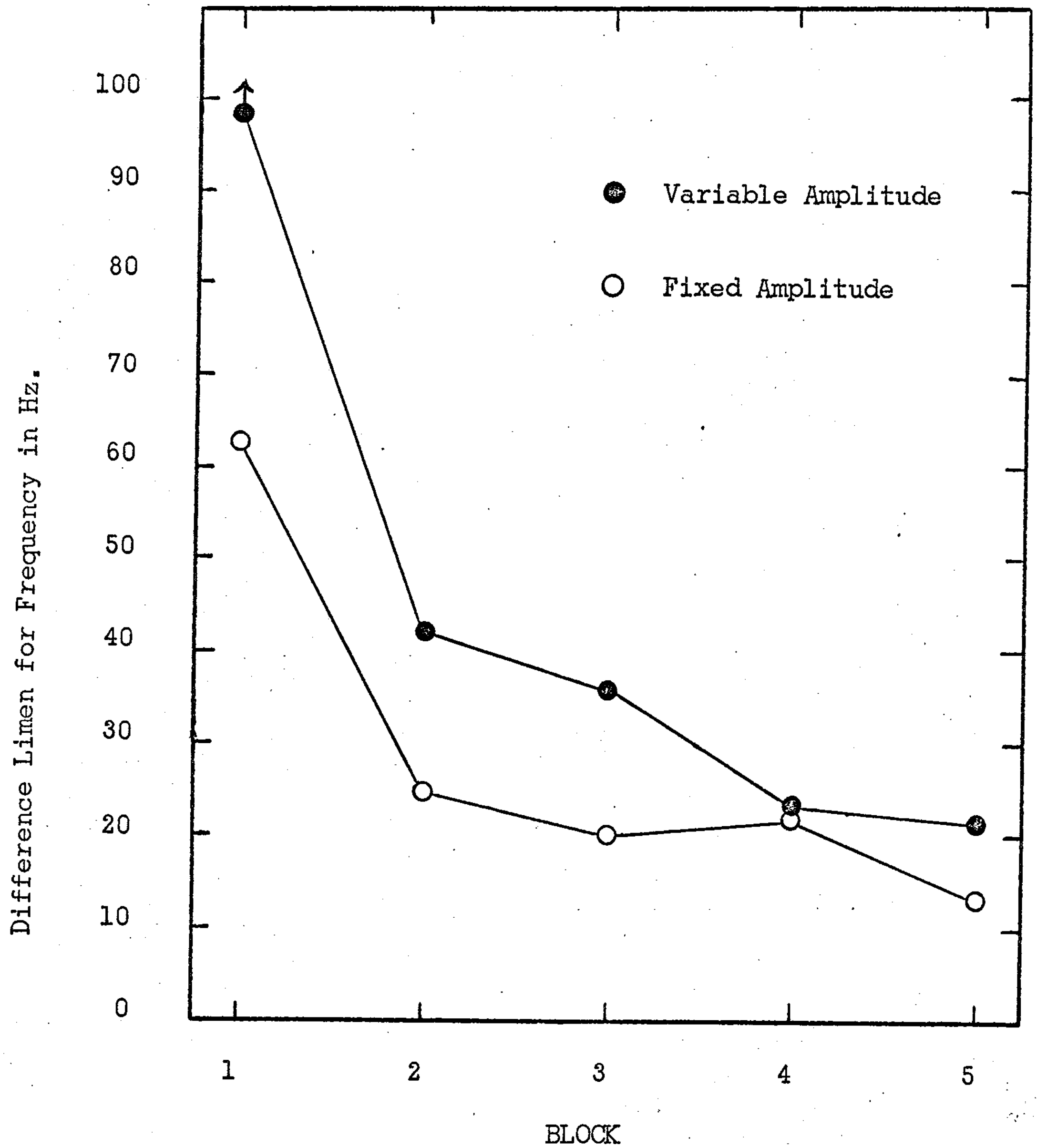


FIGURE 9. THE EFFECTS OF EXTENDED PRACTICE ON THE SIZE OF THE DIFFERENCE LIMEN FOR FREQUENCY.

experiments are interpreted to have demonstrated the thesis initially set forward in this dissertation; that is, the relatively large DLFs that hearing-impaired children show is due to lack of practice in making these discriminations and that, with practice, significant reductions in the size of DLF can be expected.

Reliability of Performance

Although the group data indicated that practice lowered the median DLF, it was also mentioned that some hearing-impaired children failed to lower their scores. To assess the reliability of individual performance from day to day, Spearman Rank Order Correlation Coefficients (Siegel, 1956) were computed between the scores of Session 1 and Session 2 and between the scores of Sessions 2 and 3. The obtained values of r_s are given below.

TABLE XXIII

CORRELATION BETWEEN PERFORMANCE ON SUCCESSIVE DAYS FOR THE TWO HEARING-IMPAIRED GROUPS

		Frequency			
		250		500	
		Session		Session	
Group	Amplitude	1-2	2-3	1-2	2-3
II	Fixed	.62	.54	.39	.60
III	Fixed	.49	.58	.76	.68
II	Variable	.52	.81	.88	.75
III	Variable	.84	.82	.70	.79

II = Hard-of-hearing
III = Deaf

The probability of obtaining correlations this large by chance alone is less than 5 percent. These data indicate that, in general, each child tends to retain his relative rank order within the group according to size of DLF and therefore it can be concluded that both groups of children showed reliable performance during the experiment.

A further indicator of the reliability of the data is found in the size of the correlation between size of DLF at 250 and 500 Hz. Recall that Houchins (1962) reported correlations between DLFs at 250 and 1000 Hz of .52 and .13 respectively for his hard-of-hearing and deaf groups. Since the test frequencies used in the present study were closer together, one might expect even higher correlations than Houchins found. Correlations were separately computed from the data obtained for each test session of the fixed-amplitude conditions. The obtained values of r_s are given below.

TABLE XXIV

CORRELATION BETWEEN SIZE OF DLF AT 250 AND 500 HZ FOR THE THREE TEST SESSIONS

	Session		
Group	1	2	3
II	.43	.53	.69
III	.26	.53	.46

II = Hard-of-hearing
III = Deaf

Except for the r_s of .26, the probability of obtaining correlations this large by chance alone is less than 5 percent. These correlations indicate that, in general, the hearing-impaired children retained approximately the same rank order according to size of DLF for both frequencies and are interpreted to be further indicators of the reliability of the subjects' performance.

Effect of Amplitude-condition

Inspection of Table XXI indicates that the median DLF is consistently larger under the variable-amplitude condition than the fixed-amplitude condition for both groups and for both test frequencies. The results of a series of Sign Tests (Siegel, 1956) indicated that the null hypothesis of no differences between amplitude conditions could be rejected at a confidence level of less than 5 percent for all test sessions at both frequencies for both groups of children.

This finding suggests the possibility that the data obtained in the fixed-amplitude conditions are not valid estimates of ability to discriminate differences in frequency. However, this finding was also not totally unexpected since the children with normal sensitivity had reported that the variable-amplitude tests seemed harder. A number of the hearing-impaired children were initially unable to separate the intensity from the frequency differences and therefore failed to discriminate correctly the differences in frequency. Nevertheless on subsequent tests these children did learn to differentiate the two sets of cues. Therefore, one possible explanation of the differences in performance under the two conditions is that the variable-amplitude condition is a perceptually more difficult task, but nevertheless, under both conditions, difference in frequency is the cue underlying performance. Implicit in this notion is that performance under the two conditions is highly correlated. Were the correlation low, then it would seem more likely that discrimination was based on different cues for each condition. Table XXV gives the correlations between the fixed and variable-amplitude conditions for each test session.

TABLE XXV

CORRELATION BETWEEN SIZE OF DLF FOR FIXED AND VARIABLE-AMPLITUDE CONDITIONS

	Frequency					
	250			500		
	Session			Session		
Group	1	2	3	1	2	3
II	.19	.67	.70	.65	.66	.70
III	.43	.65	.74	.72	.80	.61

When it is recalled that for most of the subjects the 250 Hz tests were the first exposures to the frequency discrimination task, then it is not surprising that the initial correlations are lower than the subsequent ones. Except for these initial correlations obtained at 250 Hz, the data are interpreted to support the explanation given above.

However, even though each child shows the same relative performance under both amplitude conditions, all children might not have utilized the frequency cue in the same way. For example, children who scored below the median under both conditions might actually perceive pitch. For these children differences in frequency might be recognized as differences in pitch. On the other hand, children who scored above the median might not have recognized differences in pitch and actually based their judgments on differences in loudness under both conditions.

Whether the differences in size of DLF under the two conditions actually reflect differences in the perceptual difficulty of the tests or reflect differences across subjects in how the frequency cues are perceived cannot be answered by the present experiment. Therefore, especially the data obtained under the fixed-amplitude conditions should be accepted only tentatively as providing valid estimates of ability to discriminate differences in frequency.

Comparison Between the Hard-of-Hearing and Deaf Groups

Inspection of Figure 10 shows that although there is a tendency for the deaf group to give larger median DLFs than the hard-of-hearing group, the differences between the two groups are sometimes quite small. At 250 Hz the deaf group

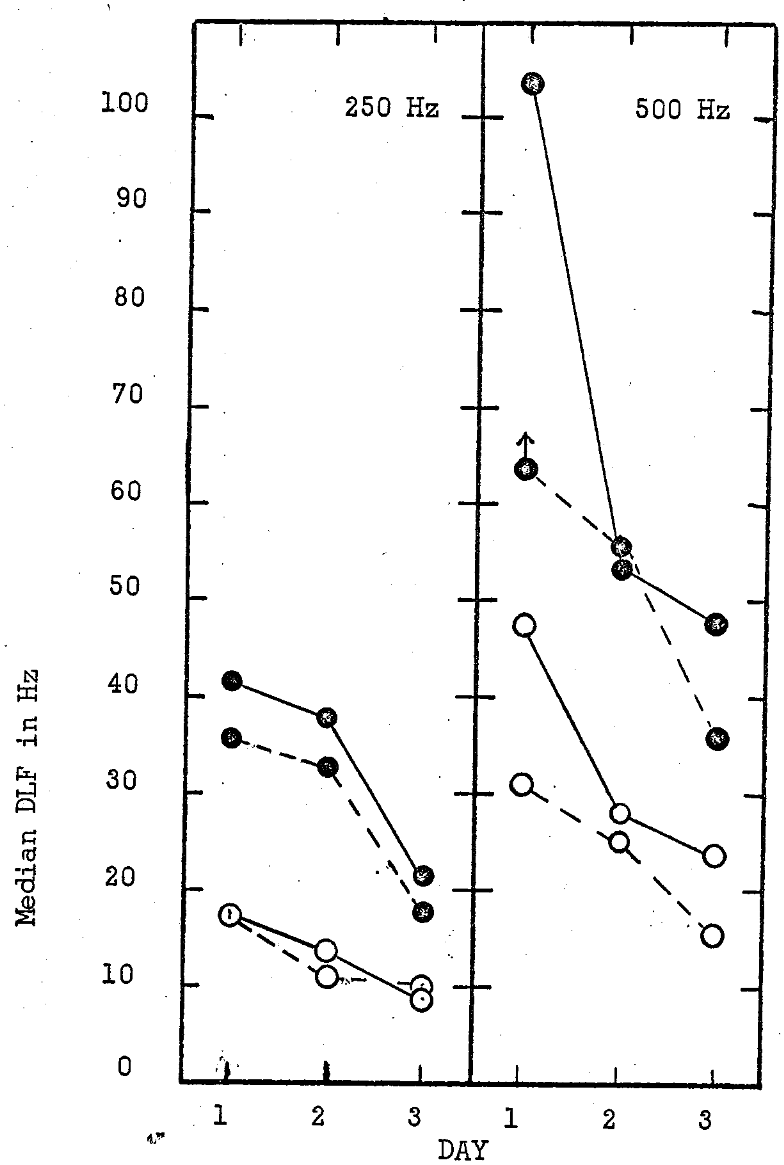


FIGURE 10. COMPARISON OF SIZE OF DIFFERENCE LIMEN FOR FREQUENCY BETWEEN THE TWO HEARING-IMPAIRED GROUPS OVER THE THREE TEST SESSIONS.

● Variable Amplitude Condition
○ Fixed Amplitude Condition

——— Deaf Group

— — — Hard-of-Hearing Group

actually shows a slightly smaller median DLF than does the hard-of-hearing group. In order to test for statistically significant differences between the two groups a series of Median Tests (Siegel, 1956) was performed. No test could be performed for session one of the 500 Hz variable amplitude condition because over half of the deaf group had a DLF greater than 128 Hz. For all other conditions the null hypothesis that the medians of the two groups differ only by chance could not be rejected.

This finding is somewhat surprising since Houchins (1962) found clear differences at both 250 and 1000 Hz. One possible explanation is that the Median Test is not powerful enough to uncover actual differences (Siegel, 1956). In order to test this notion the data were reanalyzed in a different way. The statistic used for this analysis was the median score obtained by each subject over the three test sessions for the fixed amplitude conditions. This value is considered to be the best estimate of size of DLF during a period which is characterized by unstable values of DLF.

Median Tests with these data also indicated no differences between the two groups. However, when the more powerful Mann-Whitney U Test (Siegel, 1956) was used, the null hypothesis of no difference between groups could be rejected at the 5 percent level of confidence for the 500 Hz condition, but not for the 250 Hz condition. These analyses add further support to the hypothesis that the two groups showed equivalent performance at 250 Hz. They also suggest that the differences at 500 Hz may be of marginal significance, and indicate a trend which would suggest that Hearing Level might be an increasingly important factor in determining size of DLF above 500 Hz. This latter point will be further elaborated in the next section which describes the relation between Hearing Level and size of DLF.

The Relation Between Hearing Level and DLF

The final purpose of the present experiment was to re-examine the relation between Hearing Level and DLF. The values of r_s obtained for each session of the fixed-amplitude test are given below.

TABLE XXVI

CORRELATION BETWEEN HEARING LEVEL AND SIZE OF DLF FOR HARD-OF-HEARING AND DEAF CHILDREN

	Frequency 250			Frequency 500		
	Session			Session		
Group	1	2	3	1	2	3
II	.37	.33	.34	.03	.42	.51
III	.24	.40	.22	.30	.35	.47

Values larger than .34 have a probability of 5 percent or less of occurring by chance alone.

The data obtained for the 250 Hz test do not generally permit rejection of the null hypothesis of no correlation between Hearing Level and size of DLF. This is in agreement with Houchins (1962) findings and is interpreted to indicate that for discrimination of differences in low frequencies the amount of Hearing Loss is not a significant factor.

In contrast, the data for the 500 Hz test do permit rejection of the null hypothesis for the second and third sessions. Finding no relation between the two variables on the first session agrees with the results of the pilot study. However, both groups show progressive increases in correlation as they refine their ability to discriminate differences in frequency. Obviously, the magnitude of the correlation is not high and only further experimentation could uncover the asymptotic level. Nevertheless, the reliability with which the correlation is seen indicates that at 500 Hz, Hearing Level is a factor in predicting the size of DLF.

Comparison of the Present Results with Previous Research

For the 250 fixed-amplitude condition Houchins (1962) reported that the median DLF of his group of hard-of-hearing children was 11 Hz. This is the same value obtained for the second and third test sessions of the present study. Such close agreement might seem to invalidate the argument for a practice effect because Houchin's initial median is as small as that obtained only after a practice session in the present study. However, it must be recalled that Houchins actually gave four tests but used the data from only the last two. Although he changed the values of Δf during the first three sessions, it is obvious that his subjects did practice making frequency discriminations before he collected his data.

For his deaf group, Houchins reported a median DLF of 29 Hz at 250 Hz. If the same argument with regard to a built-in practice effect is used here as was used above then his value is considerably larger than the 14 Hz median obtained for the second session of the present experiment. This discrepancy cannot be explained. However, recall that Houchins obtained both his hard-of-hearing and deaf subjects from the public school system. The present author had a similar set of conditions with the hard-of-hearing children he tested. In contrast, the present author was known by all the deaf children because they had served as subjects in the pilot studies described earlier, and because he had other social contacts with some of the subjects. This added familiarity might have served to increase the subjects' motivation to do well in the task.

Comparison of the data obtained at 500 Hz is more difficult because a comparable experiment has not been reported. Both Strizver (1958) and DiCarlo (1962) employed a "same-different" response, which is associated with smaller DLFs than the more stringent "HL or LH" response used in the present experiment. However, 18 of the present subjects also gave data in the pilot study of the previous year which also employed a "same-different" response. The average DLF of the 18 subjects in the pilot study was 34.4 Hz while the comparable average value for the first session of the present experiment was 50.0. The present data obtained for the second and third sessions indicate that even with the more stringent response, the subjects give results comparable to the smallest previously reported; this is DiCarlo's average DLF of 26 Hz.

Of course, it is conceivable that the pilot DLF-study acted as an initial practice session for the present experiment at 500 Hz. The lapse of a year between the pilot test and the present tests need not necessarily mitigate the effects of practice. Were the experiments related, then there should be a high correlation between size of DLF for the pilot study and session one of the present study. Whereas at 500 Hz the correlation between DLF for sessions one and two of the present study was .76, the correlation between the pilot study-DLF and session one was only .28. This result is interpreted to indicate that performance in the two experiments is unrelated.

Review of Results

Before discussing the results, the main findings of the present experiment are reviewed.

I. Children with normal sensitivity.

   A. Seven highly motivated children with normal sensitivity showed median DLFs at 250 and 500 Hz of less than 3 and less than 4 Hz respectively on initial tests of DLF.

   B. Median values were identical regardless of amplitude condition.

II. Children with impaired hearing.

A. Effects of practice.

1. For both hard-of-hearing and deaf children there were progressive decreases in median size of DLF over three sessions for all stimulus conditions and progressive shifts in the distributions of DLF toward smaller DLFs.

2. Statistically significant decreases in DLF were obtained under all conditions for the deaf group but under only one condition for the hard-of-hearing group.

3. When the two groups were combined, highly significant decreases in DLF were obtained for all stimulus conditions.

4. When given 10 tests of both amplitude conditions six children who initially showed large DLFs showed progressive reductions in size of DLF under both conditions. Plateaus in the learning curves were evident. However, there was no evidence that asymptotic performance had been reached.

B. Reliability of performance.

1. For both groups the correlations between performance on one day and the next was statistically significant. The moderate to high correlations indicated reliable performance within a test.

2. For both groups the correlation between performance at 250 and 500 Hz was significant. These results indicated that the relative performance of each child was similar across frequency conditions.

C. Effect of amplitude-condition.

1. For both groups, significantly smaller DLFs were obtained for the fixed-amplitude condition than for the variable-amplitude condition.
2. Significant correlations were obtained between performance under the two amplitude conditions.
3. The results of these analyses suggested differences in the perceptual difficulty of the two tests but did not rule out other possible explanations.

D. Comparison between the two hearing-impaired groups.

1. Statistical analysis indicated there were no differences in median performance for any test session or any test condition between the two groups.
2. Supplementary analyses suggested that differences between the two groups might be found at 500 Hz were it feasible to employ more powerful statistical tests.

E. Relation between Hearing Level and size of DLF.

1. In general, the correlation between Hearing

Level and size of DLF at 250 Hz was not significant. In contrast, correlations were significant at 500 Hz for the second and third test sessions. This result indicated that Hearing Level was related differently to DLF at the two frequencies.

D. Discussion

The thesis put forward in this experiment was that as a group, children with congenital hearing impairments show larger DLFs than do hearing-impaired adults because the children have had less practice in making discriminations of small differences in frequency. The data obtained from the present experiment indicate that the median DLF is approximately halved over three test sessions, but that the median value still is larger than average values reported from adults.

A small sample of children who initially showed relatively large DLFs were given further practice and it was found that after 10 sessions their scores were all below the group median for the third session of the main experiment, and furthermore there was no clear sign of asymptotic performance. It is therefore concluded that the data obtained in the experiment support the thesis. However, before the implications of the results for auditory training are discussed, two other topics require discussion. First, the data are examined in relation to their agreement with the theory of frequency discrimination proposed by Wever (1949). Second, the possibility that at least some of the data reflect the DLF for vibro-tactile discrimination is discussed.

The hair cells of the Organ of Corti and the associated auditory nerve fibers is the mechanism that codes physical information into the neural information which is finally interpreted by the brain. For low frequencies, Wever suggests that hair cells and nerve fibers respond to each cycle of the waveform, thereby transmitting a one-for-one transform of the sound wave.

Because the impulse rate of neurons is limited by their absolute and refractory phases, a direct transform cannot be maintained above approximately 400 Hz. Therefore, Wever suggests that groups of fibers take turns in synchronously firing according to a volley principle whereby although each individual neuron fires at a relatively slow rate, the entire nerve fires at a rate which remains an exact transform of the sound wave.

Nevertheless, even this process progressively breaks down as the frequency of the wave is increased. A different type of coding is made possible by the physical characteristics of the basilar membrane. The place on the membrane of maximum activity is frequency dependent. The higher the frequency, the closer is the maximum activity to the basal end of the membrane. High-frequency information is therefore coded according to place of maximum stimulation.

Wever (1949) suggests that the transition from one mode of frequency analysis to the other is a gradual one. Below about 400 Hz frequency is coded directly. From about 400 to 5000 Hz both frequency and place information are transmitted, with place becoming progressively more dominant as frequency is increased. Above 5000 Hz frequency is coded according to place alone.

To account for the loudness of sounds, Wever suggests two principles. First, within a certain range, fiber discharges increase as intensity increases. However the increased rate of firing remains in synchrony with the frequency of the stimulating sound. Second, as intensity is increased, the spatial spread of activity on the basilar membrane is increased, thereby increasing the number of nerves which fire.

Wever does not discuss the effects of hearing disorders on the discrimination of intensity and frequency in detail. However, in general he suggests that loss in sensitivity is due to reduction in the number of fibers capable of discharging. Apparently this means that some particular number of active fibers must be integrated before a sensation of sound is possible and since in a deaf listener there are fewer febers which function, greater intensity is required to activate a sufficient number. To account for recruitment and (according to Filling, 1958) the associated rapid increase in the discriminability of frequency, Wever suggests that as intensity is increased above threshold, the increased discharge rate of the fibers which initially fire, causes the sensation of loudness to increase disproportionately rapidly at first. However as an increased number of fibers are stimulated the proportionate increase in loudness decreases and approaches the normal rate.

The concepts suggested by Wever can be used to give a reasonable account of the data obtained in the present experiment. First, at 250 Hz there appeared to be no difference between the hard-of-hearing and deaf listeners in ability to discriminate differences in frequency. Since 250 Hz is well within the frequency region where frequency is transformed directly into an equivalent frequency of fiber discharges, as long as all functional fibers are functioning normally, discrimination at 250 Hz should be independent of hearing loss. Actually, according to the theory, discrimination should be normal. Therefore, finding no differences between the two groups supports the theory. Furthermore, this reasoning is consistent with the finding of a relatively low correlation between Hearing Level and size of DLF.

To further substantiate the theory, asymptotic performance of hearing-impaired children should show normal DLFs. Nevertheless, since some of the children in the present experiment showed DLFs as small as those of the normal children, it would be surprising if the hypothesis were not supported by subsequent research.

At 500 Hz, the main analysis also indicated no differences between the two groups. However, supplementary analyses suggested differences between the two groups. These findings were interpreted to indicate the beginning of a separation between the performance of the two groups. Since 500 Hz is at the lower end of the scale at which place of stimulation contributes to the encoding of frequency information, finding small differences between the two groups is again consistent with the theory.

The moderate correlation between Hearing Level and DLF is also consistent with the theory. Assuming that Hearing Level is a reflection of the number of functional fibers, then as the amount of energy required for sensation is increased an accompanying increase in spread of activity would also be assumed. This in turn, should result in a reduction in the frequency-resolving power of the ear. To further substantiate the theory, experiments which measure DLF at higher frequencies are required. For the theory to be supported, systematic increases in the correlation between Hearing Level and DLF should be found.

Finally it will be recalled that a moderate correlation was found between DLF at 250 and 500 Hz. According to Wever's theory, moderate correlations could be found between size of DLF at 250 and 500 Hz because place information is contributing relatively little information at 500

Hz and none at 250 Hz. Further support would be obtained if subsequent research showed progressively less correlation between DLF at 250 Hz and progressively higher frequencies.

Results of the present study suggested that the correlation might be higher for the hard-of-hearing group than for the deaf group. Within the framework of Wever's theory a simple rationale is not available to explain how Hearing Level would affect the correlation between performance at different frequencies. The suggested differences might simply reflect differences in the level of ability that are due to the hard-of-hearing children having had greater opportunities to practice making discriminations prior to the test.

Although the data can generally be explained by Wever's theory of frequency discrimination, the possibility cannot be overlooked that, at least for some of the children, vibrotactile sensation might have mediated some or all the information about frequency differences.

Nober (1963) recently reported the following median thresholds from deaf children when an earphone was coupled to the palm of the hand.

250	500	1000	Hz
105	111	116	dB SPL

These values are slightly higher than values previously reported by Goodfellow (1933) which were obtained at the finger tip. Calculations based on Goodfellow's data yield the following values.

250	500	1000	Hz
93	100	109	dB SPL

The majority of the deaf children received stimuli that were above both sets of values. If it is assumed that the skin of the pinna or ear canal is as sensitive to vibration as the hand, then vibro-tactile information might have influenced the performance of these children.

A search of the literature indicated that the DLF for vibro-tactile stimulation has not received as much attention as the auditory DLF. Nevertheless, some data are available. Knudsen (1928) reported DLFs at the fingertip from two subjects using stimuli delivered 50 dB above threshold. The absolute DLFs are given below.

Subject	128	256	512
1	28.2	20.5	102.4
2	39.7	25.0	179.2

Gault (1927) reported that differences of 9 percent can be discriminated for frequencies up to 600 Hz. This would indicate a DLF of 22.5 at 250 Hz and 45 at 500 Hz. Similarly, Joel (1935) reported that subjects could not discriminate 225 from 200 Hz or 450 from 400 Hz.

Goff (1967) recently criticized all previous studies on the grounds that the intensity relations between simuli were not adequately controlled. According to Goff small shifts in frequency can sometimes be interpreted by the skin as shifts in amplitude. She therefore obtained equal-intensity contours for various frequencies delivered 20 and 35 dB above threshold. Then, using equally intense tones she obtained the following DLFs.

dB SL	100	150	200	Hz
20	15	21	59	
35	17	45	96	

These data would suggest very large DLFs for 250 and 500 Hz. However, since possible amplitude artifacts were not specifically controlled in the present study the present results should be compared with results obtained prior to Goff's.

If a DLF of 20 Hz is specified for 250 Hz and 40 Hz for 500 Hz, then it is entirely possible that some children in the present experiment might have responded to vibro-tactile differences in stimulation.

In an effort to gain further information about vibro-tactile discrimination a deaf subject who showed small DLFs in the previous study was tested at 500 Hz with the ear-phone tightly coupled to the palm of the hand. Ear and hand DLFs are compared below.

	500 Hz	
	Fixed	Variable
Ear	7	7
Hand	12	15

The results are particularly surprising for the variable-amplitude condition where it might have been assumed that actual variations in amplitude would tend to randomize fixed amplitude cues associated with different frequencies.

Because these data can be used to question the validity of a conclusion that the results of the main experiment show DLFs for a hearing response, a further pilot experiment was begun. The conditions and procedures were the same as in the previous experiment except that (1) stimuli were delivered to both the ear and the palm of the hand; (2) five new versions of both the fixed- and variable-amplitude 500 Hz tapes were used; and (3) only the 500 Hz test frequency was used.

Three deaf subjects who had not served in any of the previous experiments were tested 10 times with both amplitude conditions and with the earphone alternately at the ear and the palm.

The individual data from this experiment are given in Appendix B. Inspection of these data indicate that responses are more consistent when the ear is stimulated, but nevertheless, at least for some sessions, the DLFs from the palm were also relatively small. Therefore, contamination of the main data by vibro-tactile discriminability cannot be discounted.

The experiment just described was not continued because no easy way could be found to decrease the variability of responses when the hand was stimulated. Small shifts in placement of the earphones on the palm could make the Δf either very discriminable or imperceptible. Additionally, small movements of the fingers could (1) either increase or decrease the degree of coupling between earphone cushion and skin, or (2) change the shape of the cavity below the cushion. As a consequence, although a careful definition of the discriminability of Δfs mediated by vibro-tactile sensation is necessary to evaluate the results of the main experiment, the problem if left for later study. Nevertheless, results obtained from one additional subject are given below.

Tests were made with a young adult woman who, until she was 19 years old, had normal hearing but subsequently became totally deaf after bilateral damage of the VIII nerves from surgery for removal of tumors. At the same time, partial section of the VII nerve was also required which left the subject with partial paralysis of the face. Repeated tests with the earphone over the pinna failed to elicit any response from the subject, even though touch-sensitivity of the pinna indicated that the subject was able to feel a brush hair placed lightly against various places. In contrast, responses from hand stimulation were similar to those obtained from the other subjects.

These results suggest a second alternative to an auditory response from some of the deaf children; namely, a vestibular response. Although various authors have suggested that the sacular macula (Wendt, 1951) plays a role in low-frequency hearing, conclusive evidence has not been brought forth. For the particular subject who was tested, although both cochlear and vestibular sensitivity can be assumed to be absent, whether vibro-tactile sensitivity is also absent is unknown. Nevertheless, the fact that complete section of the VIII nerve and partial section of the VII nerve can completely abolish response to sound suggests that a vestibular response from some subjects of the main experiment cannot be discounted.

One possible way to further explore vibro-tactile discriminability would be to test children with Hearing Levels greater than the maximum levels allowed in the present experiment. Children with very severe hearing losses, who are thought to show "feeling" thresholds rather than "hearing" thresholds would presumably show larger asymptotic DLFs than children who unquestionably hear the stimuli. Some support for this notion is found in the data from the one subject who showed no apparent reduction in DLF for the ear over 10 trials of both ear and hand testing. Whereas the other two subjects were quite insistent they could discriminate differences in pitch, this subject reported basing her responses on differences in loudness. This subject also showed Hearing Levels between 90 and 105 dB (ISO) at 500 Hz on three yearly tests, thereby making her the deafest subject tested.

Implications for Auditory Training. Although theoretical issues stemming from the data remain unresolved, the general procedure for giving auditory training has proven useful.

In approximately one hour of actual work time the method shows which children need extensive, moderate or little further training in discriminating differences in the low-frequency range. Concurrently, the concepts of both frequency and intensity were introduced and learned by most of the subjects. To make the procedure less time-consuming the fixed-amplitude tests could be deleted.

Tests should be extended to include 1000 and 2000 Hz. The results of these tests should lead to predictions as to which children would be expected to learn readily to discriminate between vowels, as opposed to those who would show greater difficulty; that is, the smaller the DLFs the greater the probability of high performance.

The procedure is also quite amenable to investigating the discriminability between complex sounds including vowels. One possibility would be to begin with vowels synthetically produced. Assuming that a subject could learn to differentiate between members of this set, he could then be given practice in generalizing the cues associated with each particular vowel by replacing the synthetic vowels with vowels uttered by different talkers.

The procedure is also amenable to pitch-matching practice. For example, using a recording system, a child would be required to match, by voicing, a particular tone. After attempting the match, he could listen to his performance, judge whether the match was close or not and either make another attempt or go on to the next sample.

The obvious disadvantage of the method is that it employs only small samples of auditory stimuli at any one time and thereby never gives the child the opportunity to attempt to discriminate ongoing speech. However, the method is intended to supplement, not replace, auditory training which employs amplified speech materials. Its usefulness resides in providing a method whereby certain fundamental discriminations can be learned to the maximum ability of the child. By using programmed instructional techniques the child could work by himself during those times when the teacher is working with other members of the class. It is emphasized that the present results were obtained in practice sessions which were each only 15 minutes long.

In conclusion, the present experiment has demonstrated the potential usefulness of the laboratory approach to auditory training. Further experiments using the method are required to determine its actual usefulness.

CHAPTER VI

SUMMARY

In an effort to evaluate the usefulness of psychophysical methods for auditory training, experiments dealing with the effects of duration on sensitivity and with frequency discrimination were performed. The subjects were children with hereditary and other congenital hearing impairments.

The threshold adaptation test indicated that over half of the children showed more than 5 dB threshold shift in reponse to continuous stimulation, compared to interrupted stimulation, for frequencies above 1000 Hz. Below 1000 Hz less than one-fourth of the children showed more than 5 dB shift for continuous stimulation. In general, the findings suggested that, for the group, threshold adaptation was not a significant factor to be considered when developing stimuli to be used in auditory training. Nevertheless, for individual children the presence of threshold adaptation might further limit their dynamic range of audibility.

The temporal integration test indicated that as a group, these hearing-impaired children showed less threshold shift for tones of very short durations than do normal listeners. However, some children showed normal temporal integration functions. The data also suggested that for some children, the critical duration at which threshold begins to rise for tones of decreasing duration might be shorter than normal. Also, small but statistically significant differences were found between threshold shifts at 500 and 1000 Hz. These data show that regardless of whether temporal integration is normal or not, short-duration stimuli are not as detectable as relatively longer ones and this factor must be considered when developing stimuli for auditory training.

The frequency-discrimination tests showed that, as a group, hearing-impaired children initially show relatively larger difference limens for frequency (DLFs) than either normal children or adults whose hearing became impaired after childhood. They also showed that initially many of the children confused amplitude and frequency when both varied simultaneously. However, with practice progressively more children learned to differentiate the two cues. For a combined group of hard-of-hearing and deaf children, highly significant decreases in size of DLF were found over three test sessions for both fixed- and variable-amplitude conditions. When given 10 tests of both amplitude conditions, six children who initially had large DLFs showed progressive reductions in DLF and gave no clear indication that asymptotic performance had been reached. No correlation was found between Hearing Level and size of DLF at 250 Hz; however, a moderate correlation was found at 500 Hz.

The results of this experiment indicated that repetitions of tests designed according to the method of constant stimuli was a useful training device for teaching discrimination of frequency-differences and for teaching the concepts of frequency and amplitude. Other areas of training are suggested. The final conclusion is that psychophysical tests might be useful in supplementing existing programs of auditory training and that their actual usefulness should be further explored.

APPENDIX A

INDIVIDUAL ESTIMATES OF DIFFERENCE LIMEN FOR FREQUENCY

Individual Data from Children with Normal Sensitivity				
	Frequency			
Amplitude =	Fixed	Variable	Fixed	Variable
Subject	250	250	500	500
1	< 3	5	< 4	< 4
2	< 3	< 3	6	5
3	< 3	< 3	< 4	5.5
4	< 3	3.5	24	< 4
5	< 3	< 3	6	< 4
6	4	5.5	< 4	< 4
7	9.5	< 3	< 4	< 4
Mdn	< 3	< 3	< 4	< 4

APPENDIX A--<u>Continued</u>

Individual Data from Hard-of-Hearing Children
(Fixed Amplitude)

Subject	250 Hz 1	250 Hz 2	250 Hz 3	500 Hz 1	500 Hz 2	500 Hz 3
1	17.5	36	13.3	12	25.5	20
2	19	16.5	9	30	26	15.8
3	< 3	< 3	4.5	< 4	4.8	6
4	10	11.5	4.5	38	12	7
5	9	7	18	13.5	13	20
6	< 3	5.5	4.5	7	6	7
7	5.8	4	5.5	22	6	6
8	> 48	18	10.5	37	7.8	15
9	19.5	7.5	9	44	26	24
10	26.5	45.0	39	28	40	40
11	33	4.5	< 3	22	7	5
12	30	22.5	11.5	16	28	40
13	9	7.5	11	20	30	4.7
14	14	30	10.5	> 64	48	13
15	18	9	14.0	31.5	42	34
16	10.5	9	4.5	44	15	6
17	10	11	10.5	35	> 64	40
18	5.5	11	5.5	52	15	15.5
19	> 48	41	30	> 64	14	31.1
20	36	27.5	4.5	> 64	26	19
21	21	36	11	52	38	59
Mdn	17.5	11	10.5	31.5	25.5	15.8

APPENDIX A--Continued

Individual Data from Hard-of-Hearing Children
(Variable Amplitude)

Subject	250 Hz 1	250 Hz 2	250 Hz 3	500 Hz 1	500 Hz 2	500 Hz 3
1	18	15	13.3	12	28	24
2	39	> 48	> 48	> 64	> 64	28
3	< 3	< 3	3	10	4.8	< 4
4	36	42	5.5	> 64	> 64	> 64
5	46	36	22.5	> 64	> 64	36
6	< 3	8.3	4.5	19	11	6
7	19.3	3.5	5	15	7.5	< 4
8	36	39	15	48	15.5	30
9	44	33	30	> 64	> 64	48
10	22.5	> 48	21	> 64	> 64	> 64
11	30	6.5	3	14	7	6
12	11	22.5	40	> 64	30	> 64
13	18	18	18	20	12	18.7
14	> 48	> 48	> 48	> 64	> 64	> 64
15	> 48	44	44	> 64	> 64	> 64
16	11	9.8	9	36	24	4.8
17	> 48	36	21	> 64	> 64	> 64
18	> 48	22	18	> 64	56	30
19	30	42	> 48	> 64	36	> 64
20	> 48	14	7.5	> 64	> 64	59
21	36	44	44	> 64	56	> 64
Mdn	36	33	18	> 64	56	36

APPENDIX A--Continued

Individual Data from the Deaf Group (Fixed Amplitude)

Subject	250 Hz 1	250 Hz 2	250 Hz 3	500 Hz 1	500 Hz 2	500 Hz 3
1	5.5	3	3	6	<4	12
2	37	11	39	96	27.8	24
3	22	9	18	37.5	20	20
4	14	14	4	28	19	13
5	20	56	33	96	96	118
6	36	22	21	81	28.5	59
7	20.5	28	15	29.5	28.5	12
8	18	14	9	48	56	7
9	10.5	20.5	7	19	12	24
10	18	15	9	59	49.5	27.5
11	7	5.5	5	48	56.5	20
12	33	20.5	15	>128	104	27
13	15	21	18	40	62.8	39.5
14	5.5	5.5	5.9	96	30	30
15	39	10.5	44	118	48	96
16	72	84	45	77.8	96	>128
17	42	10	9	29.5	12.5	6
18	5.5	19	5	48	28	28
19	<3	<3	<3	7	7	7
20	9	18	5.5	>128	>128	>128
21	14	7	7	7	6	5
22	>96	90	36	56	48	15.5
23	30	10.5	14	12.5	28.5	14
Mdn	18	14	9	48	28.5	24

APPENDIX A--Continued

Individual Data from the Deaf Group (Variable Amplitude)						
	250 Hz			500 Hz		
Subject	1	2	3	1	2	3
1	7.5	5.8	< 3	9.5	9.5	28
2	56	30	44	104	54	75
3	21	9	16.5	28	14	14.7
4	10.5	10	5.8	26	19	12
5	85	88	82	> 128	> 128	> 128
6	61	> 96	> 96	> 128	118	81.5
7	30	36	21	> 128	72	22
8	36	51	20	56	63	52
9	42	44	18	22	6.5	48
10	44	38	17	40	80	48
11	30	72	15	> 128	> 128	59
12	84	58	42	> 128	59	34
13	> 96	42	39	75	> 128	96
14	56	30	36	> 128	> 128	120
15	> 96	96	84	> 128	54	24
16	84	96	72	> 128	> 128	> 128
17	18	22	23.5	75	40	56
18	36	17	12	96	28.5	15
19	< 3	7	< 3	7	10	< 4
20	> 96	> 96	> 96	> 128	> 128	> 128
21	10	11.5	9.5	15.5	38	20
22	> 96	96	57	118	29.5	44
23	36	20.5	22	> 128	29.5	20
Mdn	42	38	22	104	54	48

APPENDIX B

DIFFERENCE LIMEN FOR FREQUENCY OBTAINED
FROM EAR AND HAND

Subject	1	2	3	4	5	6	7	8	9	10
Ear, Fixed Amplitude										
1	20	28	26	24	19	11	12	19	<8	11
2	84	27	54	30	16	27	36	26	29	17
3	32	39	21	45	32	32	21	32	27	27
Ear, Variable Amplitude										
1	24	32	64	40	48	96	39	56	24	21
2	128	>128	128	59	12	48	43	12	27	24
3	72	96	101	64	128	64	96	>128	64	48
Hand, Fixed Amplitude										
1	128	27	16	77	14	23	23	14	13	27
2	77	73	16	14	64	8	32	15	29	64
3	16	68	101	29	72	73	32	101	64	58
Hand, Variable Amplitude										
1	128	94	128	52	77	40	90	107	64	41
2	128	105	48	>128	107	128	128	52	64	74
3	>128	112	>128	>128	>128	>128	118	103	128	>128

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